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# ANGLO SAXON CHRONOLOGY PROJECT
# LABORATORY AND QUALITY ASSURANCE PROCEDURES AT THE QUEEN'S UNIVERSITY, BELFAST RADIOCARBON DATING LABORATORY FOR DATED SAMPLES

## SCIENTIFIC DATING REPORT

Gerry McCormac, Paula Reimer, Alex Bayliss, Michelle Thompson, Nancy Beavan, David Brown, and Stephen Hoper

ARCHAEOLOGICAL SCIENCE

ENGLISH HERITAGE

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## SUMMARY

The laboratory procedures are described that were used to produce 180 radiocarbon measurements at the Queen's University, Belfast Radiocarbon Dating Laboratory between 1999 and 2006. These samples were dated as part of the English Heritage-funded project, *Anglo-Saxon England c AD 570–720: the chronological basis*.

Ninety-five of the samples were human bone from graves containing diagnostic artefact assemblages. The remainder of the dated material comprised decadal samples of known-age Irish oak spanning the period AD 390–810. The oak measurements were carried out to provide a bespoke section of calibration curve to ensure maximum accuracy of the calibrated dates on the human remains. Two independent measurements were made on each decadal sample of oak and these were counted quasi-simultaneously with the human bones.

Further radiocarbon and stable isotope measurements undertaken during this period on samples from other projects of relevance to this study are also reported

## CONTRIBUTORS

Gerry McCormac, Paula Reimer, Alex Bayliss, Michelle Thompson, Nancy Beavan, David Brown, and Stephen Hoper

## ACKNOWLEDGEMENTS

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## ARCHIVE LOCATION

Queen's University, Belfast

## DATE OF PROJECT

1999–2009

## CONTACT DETAILS

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# 1 INTRODUCTION

The methods used for conventional radiocarbon dating by liquid scintillation spectrometry at the Queen's University, Belfast Radiocarbon Dating Laboratory (hereafter Belfast) are described in this report. It outlines the sample pre-treatment methods and describes the measures taken to safeguard the accuracy and the reproducibility of the measurements produced as part of the English Heritage funded research project, *Anglo-Saxon England c AD 570–720: the chronological basis*. Radiocarbon determinations are identified by a unique laboratory code. So, for example, UB is the code for the Queen's University Belfast, and UB-4512 is the 4,512$^{th}$ measurement produced by the laboratory. This code is the internationally-agreed identifier by which every radiocarbon determination can be traced.

Bayesian chronological modelling (Bronk Ramsey 1995; Buck *et al* 1996) has been used to combine the high-precision radiocarbon dates of human bone with sequences produced by correspondence analysis of the artefact types recovered from graves (Greenacre 1984; 1992; Høilund Nielsen 1995). The overall aim is to provide accurate estimates of archaeological chronology which span only a few decades (at 95% probability) and thereby verify the calendar dating suggested by typology. The rate of change in atmospheric $^{14}C$ in the Anglo-Saxon period makes such resolution feasible, although only within a context of precise and accurate radiocarbon measurement.

# 2 LABORATORY TECHNIQUES

Samples of human bone from skeletons included in the Anglo-Saxon project and decadal wood samples from tree-ring series, which have been dated by dendrochronology to the corresponding time period, were pre-treated to remove contamination and combusted to generate carbon dioxide ($CO_2$), which was then converted to benzene ($C_6H_6$). A phosphor is added to the benzene and radioactive disintegrations are counted by measurement of the scintillations resulting from $\beta$-particles interacting with the phosphor as the radiocarbon in the samples reverts to nitrogen. The number of radioactive disintegrations is measured for both the unknown age sample and a standard material, and from this a radiocarbon age is determined.

## 2.1 Pre-treatment

Bone samples were pre-treated by a method based on Longin (1971). Each sample is broken into small pieces and placed in a 5l beaker under 2% hydrochloric acid (HCl) for demineralisation. The pH is checked daily and, if the acid is consumed, it is decanted and replaced with fresh acid. The process typically takes 5 days. The liquid is then discarded and the solid residue is washed with deionised water to remove calcium ions thus helping to prevent the formation of humates. The sample is then placed in 0.01M HCl and heated to 80–90°C for 5–18 hours to extract collagen in the lysing process. The liquid containing the collagen is then vacuum filtered through glass microfibre paper (70mm GF/D grade)

(Fig 1) before being poured into an evaporating basin and dried in a moisture extraction oven at 100°C (Fig 2). A repeat lysing step is performed on the solid residue to extract further collagen from the sample. The pH of the dried protein is raised (a modification to the Longin method) by reconstituting the sample in deionised water. This precipitates acid-soluble solid impurities before the sample is again dried in a moisture extraction oven.

Wood samples were chemically pre-treated to holocellulose using the method outlined by Green (1963). The samples from each decade are cut into matchstick size pieces using a hammer and chisel or planed before being granulated in a Wiley intermediate mill (20 mesh). They are placed in acidified sodium chlorite ($NaClO_2$) solution ('bleach') overnight before being drained and heated in 4% HCl for one hour. Samples are then vacuum filtered through glass microfibre paper using deionised water until neutral pH after which they are dried in a moisture extraction oven.

*Figure 1: Vacuum filtration of the liquid containing the collagen (photo Amanda Grieve)*

*Figure 2: Collagen after moisture extraction (photo Amanda Grieve)*

## 2.2 Combustion

The pre-treated material is combusted in a stream of ultra pure oxygen in a positive pressure system (*c* 1.5atm) that has been purged by ultra pure nitrogen (this prevents the sample from being contaminated by atmospheric $CO_2$ which contains a small fraction of radiocarbon) (Fig 3). The resultant gas is passed through a furnace containing copper oxide at 600°C to convert any carbon monoxide (CO) present to $CO_2$. The gas is purified by the removal of halides at two stages by means of silver wool at 400°C. Other volatile gaseous by-products are oxidised and removed by passing the gas through three traps containing a saturated solution of potassium permanganate ($KMnO_4$). Water is removed from the gas using three 'cold' traps of dry ice-methanol mixture. The purified and dried $CO_2$ is collected in a trap under liquid nitrogen (Fig 4). Glass-metal liners provide a temperature gradient that limits the amount of carrier oxygen frozen, allowing a longer combustion time into the trap and faster evacuation of excess oxygen when the system is opened to vacuum. The frozen $CO_2$ is expanded and trapped in a metal storage vessel ('bomb'). A schematic diagram summarising the combustion process is provided in Figure 5.

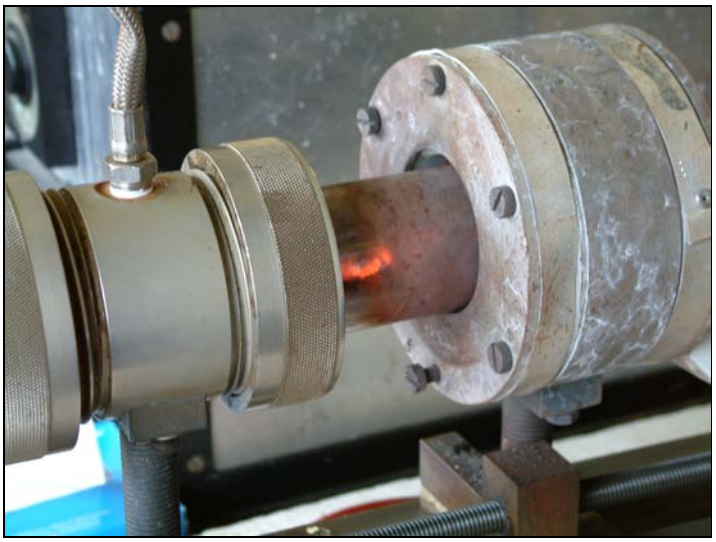

*Figure 3: Sample combustion (photo Amanda Grieve)*

*Figure 4: Freezing the CO2 in a liquid N2 trap (@~ -150°C) (photo Amanda Grieve)*

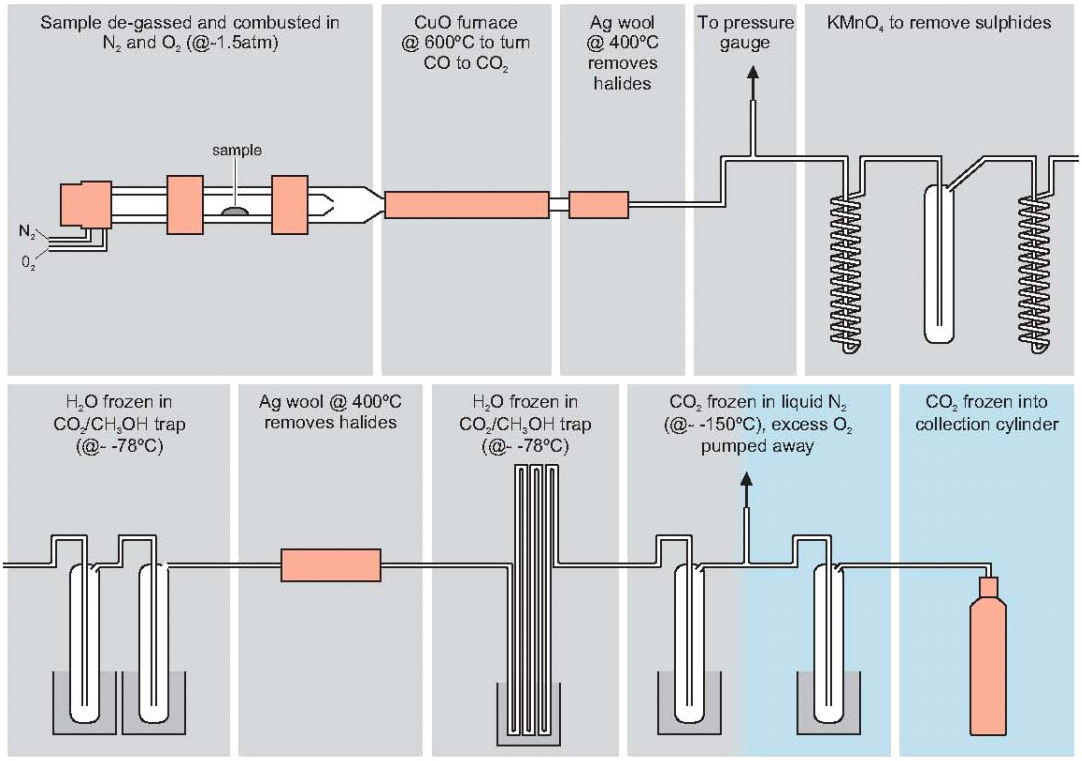


*Figure 5: Schematic diagram summarising the steps in the combustion process (John Vallender)*

## 2.3 Fractionation Correction

A sub-sample of the $CO_2$ is taken to measure the ratio of $^{13}C$ to $^{12}C$ in a mass spectrometer (VG 602e Micromass). In nature, there is a tendency for the lighter carbon isotope ($^{12}C$) to be taken up preferentially, and so plants and animals may have a lower $^{14}C$ concentration than the atmosphere. This effect is known as fractionation (Bowman 1990, 20). Fractionation may also occur during laboratory handling due to incomplete reactions. The ratio of $^{12}C$ to $^{13}C$ ($\delta^{13}C$) is measured with respect to an internationally agreed standard (VPDB; Craig 1953; 1957), and is usually expressed in parts per thousand (per mil.; ‰). As $^{13}C$ does not decay radioactively, the $^{13}C/^{12}C$ ratio remains constant, and can be used to estimate the original uptake of $^{14}C$, because the fractionation of $^{14}C$ should be double that of $^{13}C$. The $\delta^{13}C$ value is incorporated into the calculation of the radiocarbon age (Stuiver and Polach 1977). If this correction was not made, the radiocarbon measurement could be anomalously old.

## 2.4 Benzene Synthesis

The $CO_2$ is converted in an evacuated system to the carbon-rich liquid, benzene ($C_6H_6$) (Fig 6).

*Figure 6: Benzene synthesis (photo Amanda Grieve)*

A sequence of reactions is involved. First the $CO_2$ reacts with molten ultra pure lithium (Li) at 600°C in a vessel (316 steel) according to the equation:

$2CO_2 + 12Li \rightarrow Li_4C_2 + 4\ Li_2O$

Radon (222Rn) free water is then added to the cooled vessel, producing acetylene ($C_2H_2$) and by-products as follows:

$Li_4C_2 + 4H_2O \rightarrow C_2H_2 + 4LiOH + H_2$

Water vapour is removed from the resultant $C_2H_2$ in a dry ice-methanol cold trap. The $C_2H_2$ is then frozen and the hydrogen (H2) is removed under vacuum. The $C_2H_2$ is then allowed to sublime slowly through beads coated with sodium hydroxide (NaOH), which removes any remaining moisture, and then orthophosphoric acid ($H_3PO_4$), which removes

ammonium compounds. The final step is the trimerisation of the $C_2H_2$ to $C_6H_6$ which is accomplished over a chromium oxide ($CrO_3$) catalyst at 40°C (Fig 7). The benzene is collected and stored for at least three weeks to allow any $^{222}Rn$ to decay. This is a contaminant radio-isotope with a short half-life which derives from the catalyst.

A schematic diagram summarising the conversion of the $CO_2$ to $C_6H_6$ is provided in Figure 8.

*Figure 7: Loading the chromium oxide catalyst to convert the acetylene to benzene (photo Amanda Grieve)*

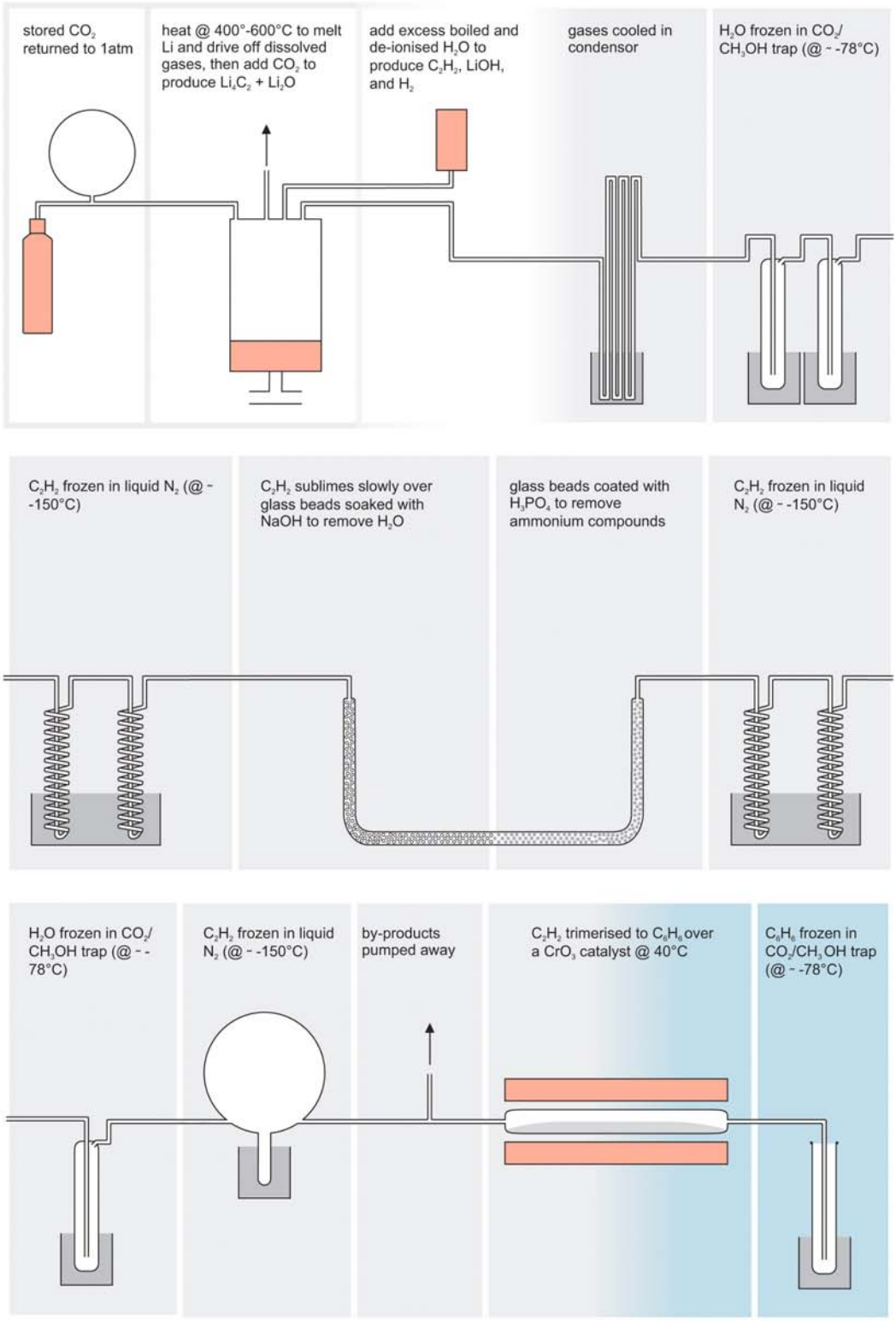


*Figure 8: Schematic diagram summarising the steps in the benzene synthesis process (John Vallender)*

## 2.5 Liquid Scintillation Counting

Once the radon has decayed, the sample benzene is thawed and transferred into a low-potassium glass vial for counting in the liquid scintillation spectrometer. Vials are already pre-selected for each counter according to optical quality, uniformity of glass and weight range, and all have undergone tests using backgrounds and oxalic acid standards. They have been matched with a counting cap that minimizes weight loss during the counting period (McCormac *et al* 2001). A precise amount of scintillant (butyl-PBD) is required according to the weight of benzene. This phosphoric compound dissolves to create a 'counting cocktail' and produces a light emission (photon) when a β- particle is emitted by a $^{14}C$ atom as it decays. The sample is transferred to the counting vial under a fume hood using a pipette/syringe and a five figure balance (Fig 9). It is essential for the calculation of the radiocarbon age that the weights of the benzene and the scintillant are known precisely. For this reason specially designed vial caps are used at every stage to minimize loss of the volatile benzene by evaporation (Pearson 1983). Counting is not started on the prepared vials until the day after the scintillant is added to the benzene, and they are re-weighed before they are loaded into a counter, to ensure that there are no undetected leaks from the vials before counting begins. Weights are monitored weekly throughout the counting period to track benzene loss.

*Figure 9: Preparing the benzene sample for counting (photo Amanda Grieve)*

Vials are placed in the liquid scintillation spectrometer along with known-activity and background standards (Fig 10). All samples were counted in LKB Wallac 1220 scintillation spectrometers. These optimised, low-level, high precision counters are set up and closely monitored for stability and performance (McCormac 1992; Wilson *et al* 1995; McCormac *et al* 2001). A schematic diagram of a counter is shown in Figure 11. Samples are counted alongside the international reference material, Oxalic Acid II (Mann 1983). Radiocarbon-free ultra pure benzene (from a petro-chemical source) is counted in each machine to monitor background activity. Each spectrometer counts two modern and two background standards. Counts from these standards are used in the calculation of the resulting radiocarbon age.

*Figure 10: Loading prepared vials into the liquid scintillation spectrometer (photo Amanda Grieve)*

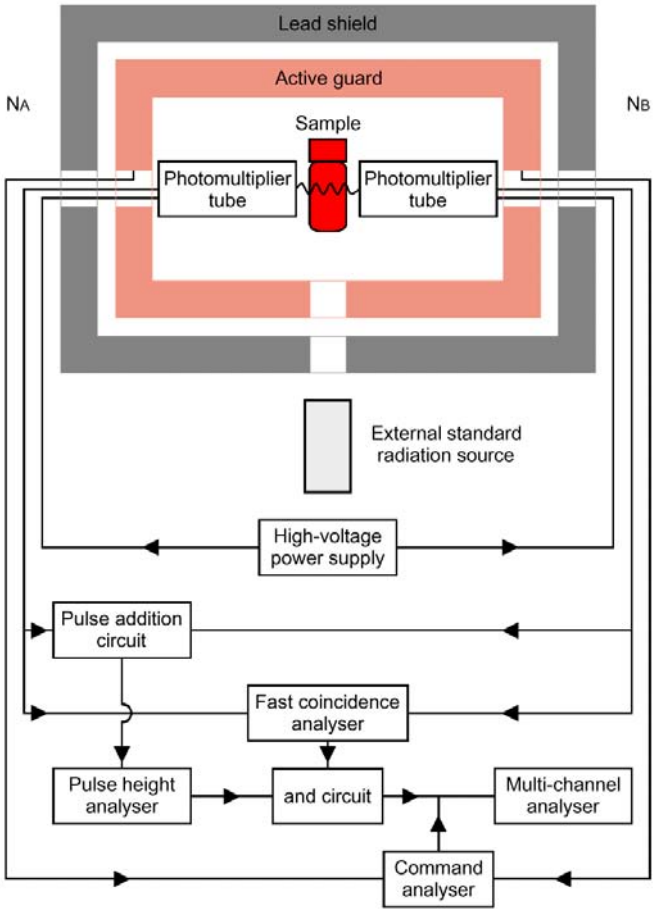


*Figure 11: A schematic diagram of a liquid scintillation spectrometer (John Vallender)*

The vial is positioned between two photomultiplier tubes which detect the light emissions. If both tubes register a pulse simultaneously and the energy of the combined pulse is within the expected range for radiocarbon, a count is recorded in a multi-channel analyser.

Passive and active shielding is employed to distinguish between sample counts (derived from the radiocarbon in the sample as it decays) and background counts (derived from background radiation). The detector assembly is enclosed in 0.2m thick lead casing to absorb background radiation. Active shielding is provided by a mineral oil-based scintillator known as the 'guard'. The photons produced by background radiation events are also detected by two photomultiplier tubes within the guard. If these pulses are coincident with counts in the detector assembly, then the sample counts are discarded as they probably came from background radiation.

Two further checks are available to ensure the validity of the detected pulses. First, the energy spectrum of the pulse is measured to ensure that it has not shifted with respect to the spectra obtained from calibration standards. Second, the sample is irradiated by an external radiation source, radium ($^{226}$Ra) measured quasi-continuously. This produces a flood of photons with a range of energies. If the benzene has a low level of impurities then the end point of this energy distribution will fall within a specific range. The set-up of counters labelled, Q1, Q3, and Q4 is as described in McCormac (1992), that of counters Q2, Q6, and Q7 is as described in McCormac *et al* (2001).

## 3 CALCULATION OF THE RADIOCARBON AGE

Once a sample has accumulated more than 250,000 counts, an age calculation can be made based on the following equation:

$$T = -\frac{T_{½}}{\ln 2} \ln (A^{14}/A^{14}_{o})\ yr = -8033 \ln (A^{14}/A^{14}_{o})\ yr$$

where ln is the natural logarithm (to base e), $A^{14}$ is the measured activity of the sample (in counts per minute per gram), and $A^{14}_{o}$ is the original $^{14}$C activity as defined by the activity of the modern standard (by convention this equation uses a half-life of 5568 years, rather than the actual half-life of 5730 years). Normal background activity is accounted for in the overall calculation as well as background contributed by the processing of the sample through the benzene line (McCormac *et al* 1993). Corrections for fractionation ($\delta^{13}$C) and for spectral shifts are also factored in (McCormac 1992).

A conventional radiocarbon age is accompanied by a standard error. This is based on the accumulated counts for the sample, oxalic acid, and background material (Stuiver and Polach 1977). Other corrections are applied, to account for other sources of error introduced, for example, by laboratory processing (Pearson 1980; Pearson *et al* 1986; McCormac *et al* 1993). A laboratory error multiplier (K) is also applied as a measure of the laboratory reproducibility, incorporating the errors resulting from gas preparation, sample loading, memory effects, and counting statistics (Pearson and Stuiver 1986, 839). 'K' is defined as the actual standard error divided by the quoted standard error and is usually generated through replicate measurement of standard or known-age material. For the analyses reported as part of this project a laboratory error multiplier of 1.25 has been applied. This is slightly more conservative than the 1.23 reported for the 1986 calibration data from Belfast (Pearson *et al* 1986).

## 4 CALIBRATION

The rate of production of radiocarbon in the atmosphere is not constant. Long term variations in the production rate correspond with changes in the strength of the earth's magnetic field and short term variations are linked to sunspot activity. The effect of this is that a radiocarbon 'year' is not equivalent to a calendar year and hence a calibration

process is necessary. The ability for absolute and precise dating of naturally occurring materials which exhibit annual growth patterns (eg tree rings) has made calibration of the radiocarbon time scale possible. Calibration curves have been produced and allow conversion between conventional radiocarbon ages and calendar dates. Variation in the concentration of $^{14}C$ in the biosphere over time can be seen in the secular variation and 'wiggles' on calibration curves. A general introduction to radiocarbon calibration can be found in Aitken (1990), further details of the currently internationally agreed calibration curve can be found in Reimer *et al* (2004).

As part of the Anglo-Saxon project, wood samples from the time period under study were processed in the laboratory alongside the samples of human bone. As well as addressing the issue of calibration by refining the existing data, the exercise also provides an additional measure of quality control on the samples of unknown age.

# 5 KNOWN-AGE WOOD SAMPLES

Decadal wood samples from a section of the Irish oak tree-ring chronology were measured specifically for the Anglo-Saxon period under study. Bi-decadal samples from this chronology had been previously measured and included in the calibration series (Pearson *et al* 1986). In this study, decadal samples were replicated to ensure internal consistency by dividing blocks of wood into two for separate measurement. In addition, to study the effect of sample combustion, a comparison was made of samples separated before combustion with those separated after combustion. Initially decadal measurements were completed for the period AD 495–725 (McCormac *et al* 2004) which were included in the INTCAL04 calibration curve (Reimer *et al* 2004), and later further measurements were made extending the curve in both directions to cover the period AD 395–805 (McCormac *et al* 2008).

## 5.1 Dendrochronology

In total forty-two 100g samples of oak (*Quercus* spp.) from a series of decades centred on AD 394.5 to AD 804.5 were processed by the laboratory. The majority of the wood samples came from three sites located in the southern part of Ireland. Samples with decades centred between AD 394.5 and AD 564.5 were from Little Island, Co. Cork (51° 53' N and 8° 55' W), except for decade AD 554.5, a replacement sample, which came from Lemanaghan, Co. Offaly (53° 17' N and 7° 45' W). Samples with decades centred between AD 574.5 and AD 724.5 were from Brabstown, Co. Kilkenny (52° 40' N and 7° 24' W). Both the Little Island and the Brabstown samples have been used before in high precision radiocarbon calibration (McCormac *et al* 1994, tables 1 and 2). The extension of this exercise into the eighth and early ninth centuries AD raised some difficulties. This is a period where there are fewer trees available in the Belfast tree-ring chronology. Fewer trees and requests for samples for various radiocarbon calibration exercises over a number of years have lead to reduced availability of the required weight of wood for conventional radiometric dating. Two samples, from a section of chronology that had not

previously been used for radiocarbon calibration from Cappagh South, Co. Clare (52° 44' N and 8° 46' W) were used to cover the period from AD 735 to AD 805. Details of the wood samples dated are given in Table 1.

*Table 1: Decadal wood samples provided for the Anglo-Saxon chronology project*

| Decade centred | Weight | Sample number | Site name | Date supplied | Laboratory Numbers |
|---|---|---|---|---|---|
| AD 804.5 | 108g | Q9309 | Cappagh South | 27/01/2004 | UB-6121–22 |
| AD 794.5 | 110g | Q9309 | Cappagh South | 27/01/2004 | UB-6119–20 |
| AD 784.5 | 118g | Q9309 | Cappagh South | 27/01/2004 | UB-6117–8 |
| AD 774.5 | 112g | Q9309 | Cappagh South | 27/01/2004 | UB-6115–16 |
| AD 764.5 | 108g | Q9308 | Cappagh South | 27/01/2004 | UB-6113–14 |
| AD 754.5 | 100g | Q9308 | Cappagh South | 27/01/2004 | UB-6111–12 |
| AD 744.5 | 100g | Q9308 | Cappagh South | 27/01/2004 | UB-6109–10 |
| AD 734.5 | 100g | Q9308 | Cappagh South | 27/01/2004 | UB-6107–8 |
| AD 724.5 | 105g | Q3693 | Brabstown | 18/01/1999 | UB-4409–4410 |
| AD 714.5 | 105g | Q3693 | Brabstown | 18/01/1999 | UB-4407–8; UB-5232 |
| AD 704.5 | 108g | Q3693 | Brabstown | 18/01/1999 | UB-4405–6 |
| AD 694.5 | 101g | Q3693 | Brabstown | 18/01/1999 | UB-4403–4 |
| AD 684.5 | 109g | Q3693 | Brabstown | 18/01/1999 | UB-4401–2 |
| AD 674.5 | 103g | Q3693 | Brabstown | 18/01/1999 | UB-4399–4440 |
| AD 664.5 | 103g | Q3693 | Brabstown | 18/01/1999 | UB-4397–8 |
| AD 654.5 | 104g | Q3693 | Brabstown | 18/01/1999 | UB-4395–6 |
| AD 644.5 | 101g | Q3693 | Brabstown | 18/01/1999 | UB-4393–4 |
| AD 634.5 | 108g | Q3693 | Brabstown | 18/01/1999 | UB-4391–2 |
| AD 624.5 | 105g | Q3693 | Brabstown | 18/01/1999 | UB-4389–90 |
| AD 614.5 | 108g | Q3693 | Brabstown | 18/01/1999 | UB-4387–8 |
| AD 604.5 | 88g | Q3693 | Brabstown | 18/01/1999 | UB-4385–6 |
| AD 604.5 | 17g | Q3693/Q3685 | Brabstown | 19/01/1999 | |
| AD 594.5 | 109g | Q3693/Q3685 | Brabstown | 19/01/1999 | UB-4383–4 |
| AD 584.5 | 63g | Q3693/Q3685 | Brabstown | 19/01/1999 | UB-4381–2 |
| AD 574.5 | 102g | Q3693/Q3685 | Brabstown | 19/01/1999 | UB-4379–80 |
| AD 564.5 | 104g | Q3676/Q3679/Q3674 | Little Island | 26/01/2001 | UB-4616–17 |
| AD 554.5 | - | Q9795 | Lemanaghan | - | UB-4618–19 |
| AD 544.5 | 168g | Q3676 | Little Island | 26/01/2001 | UB-4620–1 |
| AD 534.5 | 126g | Q3676 | Little Island | 26/01/2001 | UB-4622–3 |
| AD 524.5 | 109g | Q3676/Q3681 | Little Island | 26/01/2001 | UB-4624–5 |
| AD 514.5 | 107g | Q3676/Q3681 | Little Island | 26/01/2001 | UB-4626–7 |
| AD 504.5 | 106g | Q3676/Q3681 | Little Island | 26/01/2001 | UB-4628–9 |
| AD 494.5 | 103g | Q3676/Q3681 | Little Island | 26/01/2001 | UB-4630–1 |
| AD 484.5 | 72g | Q3676 | Little Island | 18/06/2003 | UB-4933–4 |
| AD 474.5 | 96g | Q3676 | Little Island | 18/06/2003 | UB-4935–6 |
| AD 464.5 | 108g | Q3676 | Little Island | 18/06/2003 | UB-4937–8 |
| AD 454.5 | 108g | Q3676 | Little Island | 18/06/2003 | UB-4939–40 |
| AD 444.5 | 103g | Q3676 | Little Island | 18/06/2003 | UB-4941–2 |
| AD 434.5 | 100g | Q3676 | Little Island | 18/06/2003 | UB-4943–4 |
| AD 424.5 | 103g | Q3676 | Little Island | 18/06/2003 | UB-4945–6 |
| AD 414.5 | 103g | Q3676 | Little Island | 18/06/2003 | UB-4947–8 |
| AD 404.5 | 104g | Q3676 | Little Island | 18/06/2003 | UB-4949–50 |
| AD 394.5 | 113g | Q3676 | Little Island | 18/06/2003 | UB-4951–2 |

### 5.1.1 Dendrochronology methodology

Tree-ring dating was carried out using the methodology described by Baillie (1982). The samples were prepared by polishing the surface with various grades of emery paper. The tree-ring pattern was highlighted with chalk so that the spring and summer pores retain the chalk and provide better visual definition of the ring widths under the microscope.

Measurement of the tree-ring pattern was carried out using a measuring stage. This machine measures the annual growth ring widths in 1/50mm. The tree-ring series obtained from the samples were plotted on graph paper for visual comparisons. The data obtained were also checked statistically with the Belfast tree-ring chronology for Ireland and with regional and site chronologies. Correlation values in Table 2 were obtained using the cross-dating program Cross84 (Munro 1984). All the samples used in this exercise had extremely high or very significant correlation values with regional or site master chronologies from Ireland.

*Table 2: Tree-ring cross-matches from the site sequence from Little Island, Co. Cork (***=extremely significant match; **=very significant match; *=significant match; nsm=non-significant match)*

| Site chronology name | Correlation Value |
|---|---|
| Little Island, Co. Cork | |
| Lemanaghan, Co. Offaly (Brown pers comm) | 6.03*** |
| Ballydaly, Co. Offaly (Brown pers comm) | 5.70*** |
| Nendrum, Co. Down (McErlean and Brown 2007) | 5.32*** |
| Teeshan, Co. Antrim (Baillie 1982, 188–90) | 4.69** |
| Brabstown, Co. Kilkenny (Baillie 1982, 188–90) | 3.94nsm |
| Brabstown | |
| Ballyroe, Co. Wexford (Brown pers comm.) | 8.54*** |
| Ballyrafton, Co. Kilkenny (Baillie 1982, 186–92) | 7.44*** |
| Newtown, Co. Tipperary (Brown pers comm) | 7.18*** |
| Ballygeardra, Co. Kilkenny (Baillie 1982, 186–92) | 6.29*** |
| Ballygormill South, Co. Laois (Brown pers comm) | 5.98*** |
| Cappagh South, Co. Clare | |
| Newtown, Co. Tipperary (Brown pers comm) | 6.12*** |
| Ballyroe, Co. Wexford (Brown pers comm) | 6.04*** |
| Brabstown, Co. Kilkenny (Baillie 1982,186–92) | 5.36*** |
| Ballygeardra, Co. Kilkenny (Baillie 1982, 186–92) | 4.89*** |
| Lemanaghan, Co. Offaly | |
| Ballydaly, Co. Offaly (Brown pers comm) | 12.96*** |
| Ballykillen, Co.Offaly (Baillie 1982,186–92) | 8.03*** |
| Deer Park, Co. Antrim (Brown pers comm) | 6.29*** |
| Little Island, Co. Cork (Brown pers comm) | 6.05*** |

### 5.1.2 Little Island tree-ring chronology

A mean tree-ring master chronology was formed using the measurements from eight samples obtained from this mill structure. This chronology is 370 years in length. Extremely significant and consistent correlation values were found with a number of site chronologies from southern Ireland (Table 2). These results indicate that the Little Island chronology dates from AD 261 to AD 630.

### 5.1.3 Brabstown tree-ring chronology

A mean master was formed using the measurements of six structural timbers from the Brabstown horizontal mill. This chronology is 333 years in length. It was compared with a series of site chronologies from Ireland as shown in Table 2. Extremely significant and consistent correlation values were found. The results indicate that the Brabstown chronology dates from AD 549 to AD 881.

### 5.1.4 Cappagh South samples

The timbers from Cappagh South, Co. Clare are from two naturally preserved riverside oaks. These series cross-match with each other with a t-value of 7.23 (Munro 1984). Evidence for the dating of the two-timber mean is provided in Table 2. These results indicate that sample Q9308 dates from AD 630 to AD 821, while sample Q9309 dates from AD 745 to AD 895.

### 5.1.5 Lemanaghan tree-ring chronology

A mean master was formed using the measurements from 10 structural timbers from the Lemanaghan trackways. This chronology is 364 years in length. It was compared with a series of site chronologies from Ireland as shown in Table 2. Extremely significant and consistent correlation values were found. The results indicate that the Lemanaghan chronology dates from AD 288 to AD 652.

## 5.2 Radiocarbon Ages from Known-age Wood

For decades AD 495–805, samples were pre-treated before being divided into pairs for separate combustion; samples from decades AD 395–485 were pre-treated and combusted before pair separation at the benzene synthesis stage (see Section 5.3 below). Each sample from the replicate pairs from the same decade was counted in a separate batch in the spectrometers to maximise the independence of the radiocarbon determinations. A replicate measurement was made for the decade centred on AD 714.5

in 2006 (UB-5232). This sample was excess cellulose from UB-4407–8, pre-treated in 1999, but combusted and synthesised to benzene separately in 2006.

Full details of all the radiocarbon results from the known-age wood samples are provided in Table 3. The results are represented graphically in Figure 12.

***Table 3: Radiocarbon ages and $\delta^{13}C$ values for decadal wood samples dated as part of the Anglo-Saxon chronology project***

| | | Sample 1 | | | Sample 2 | | |
|---|---|---|---|---|---|---|---|
| Decade Centred (AD) | Site Details | Radiocarbon Age (BP) | error | $\delta^{13}C$ (‰) | Radiocarbon Age (BP) | error | $\delta^{13}C$ (‰) |
| 394.5 | Little Island, Co. Cork | 1645 | 20 | –24.9 | 1659 | 13 | –24.9 |
| 404.5 | Little Island, Co. Cork | 1649 | 20 | –25.4 | 1611 | 13 | –25.4 |
| 414.5 | Little Island, Co. Cork | 1621 | 19 | –24.7 | 1635 | 21 | –24.7 |
| 424.5 | Little Island, Co. Cork | 1598 | 19 | –25.3 | 1560 | 21 | –25.3 |
| 434.5 | Little Island, Co. Cork | 1530 | 19 | –24.4 | 1529 | 21 | –24.4 |
| 444.5 | Little Island, Co. Cork | 1591 | 19 | –24.8 | 1539 | 21 | –24.8 |
| 454.5 | Little Island, Co. Cork | 1549 | 19 | –23.9 | 1554 | 21 | –23.9 |
| 464.5 | Little Island, Co. Cork | 1589 | 21 | –24.9 | 1589 | 22 | –24.9 |
| 474.5 | Little Island, Co. Cork | 1574 | 21 | –25.8 | 1537 | 21 | –25.8 |
| 484.5 | Little Island, Co. Cork | 1559 | 21 | –26.2 | 1504 | 21 | –26.2 |
| 494.5 | Little Island, Co. Cork | 1650 | 21 | –25.1 | 1595 | 20 | –25.0 |
| 504.5 | Little Island, Co. Cork | 1611 | 21 | –25.2 | 1606 | 20 | –25.0 |
| 514.5 | Little Island, Co. Cork | 1556 | 21 | –24.5 | 1595 | 20 | –25.0 |
| 524.5 | Little Island, Co. Cork | 1607 | 21 | –24.8 | 1613 | 20 | –24.7 |
| 534.5 | Little Island, Co. Cork | 1571 | 20 | –24.5 | 1598 | 20 | –24.5 |
| 544.5 | Little Island, Co. Cork | 1538 | 20 | –24.0 | 1572 | 20 | –24.3 |
| 554.5 | Lemanaghan, Co. Offaly | 1511 | 17 | –26.9 | 1534 | 19 | –26.6 |
| 564.5 | Little Island, Co. Cork | 1524 | 20 | –24.5 | 1510 | 20 | –24.4 |
| 574.5 | Brabstown | 1475 | 24 | –23.8 | 1499 | 24 | –23.8 |
| 584.5 | Brabstown | 1486 | 24 | –24.8 | 1464 | 24 | –24.7 |
| 594.5 | Brabstown | 1504 | 24 | –24.6 | 1442 | 24 | –24.6 |
| 604.5 | Brabstown | 1439 | 24 | –24.0 | 1478 | 24 | –24.1 |
| 614.5 | Brabstown | 1423 | 24 | –23.8 | 1452 | 24 | –23.8 |
| 624.5 | Brabstown | 1425 | 24 | –24.3 | 1451 | 24 | –24.2 |
| 634.5 | Brabstown | 1415 | 22 | –24.3 | 1432 | 22 | –24.3 |
| 644.5 | Brabstown | 1424 | 22 | –24.7 | 1425 | 22 | –24.7 |
| 654.5 | Brabstown | 1373 | 22 | –25.0 | 1371 | 22 | –25.1 |
| 664.5 | Brabstown | 1343 | 22 | –25.0 | 1321 | 22 | –25.4 |
| 674.5 | Brabstown | 1305 | 22 | –26.0 | 1285 | 22 | –26.0 |
| 684.5 | Brabstown | 1281 | 24 | –25.6 | 1281 | 24 | –25.5 |
| 694.5 | Brabstown | 1249 | 24 | –25.7 | 1271 | 24 | –25.8 |
| 704.5 | Brabstown | 1264 | 24 | –25.7 | 1263 | 24 | –25.9 |
| 714.5[1] | Brabstown | 1238 | 22 | –25.2 | 1266 | 22 | –25.2 |
| 724.5 | Brabstown | 1279 | 22 | –25.5 | 1249 | 22 | –25.5 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 734.5 | Cappagh South, Co. Clare | 1216 | 16 | –25.1 | 1211 | 22 | –24.9 |
| 744.5 | Cappagh South, Co. Clare | 1294 | 16 | –25.0 | 1248 | 23 | –25.8 |
| 754.5 | Cappagh South, Co. Clare | 1262 | 16 | –26.3 | 1268 | 29 | –25.9 |
| | | Sample 1 | | | Sample 2 | | |
| Decade Centred (AD) | Site Details | Radiocarbon Age (BP) | error | $\delta^{13}C$ (‰) | Radiocarbon Age (BP) | error | $\delta^{13}C$ (‰) |
| 764.5 | Cappagh South, Co. Clare | 1275 | 16 | –26.9 | 1233 | 23 | –25.9 |
| 774.5 | Cappagh South, Co. Clare | 1154 | 20 | –25.0 | 1116 | 22 | –25.0 |
| 784.5 | Cappagh South, Co. Clare | 1141 | 20 | –26.2 | 1143 | 22 | –26.3 |
| 794.5 | Cappagh South, Co. Clare | 1145 | 20 | –25.8 | 1195 | 22 | –25.8 |
| 804.5 | Cappagh South, Co. Clare | 1184 | 20 | –25.7 | 1150 | 22 | –25.7 |

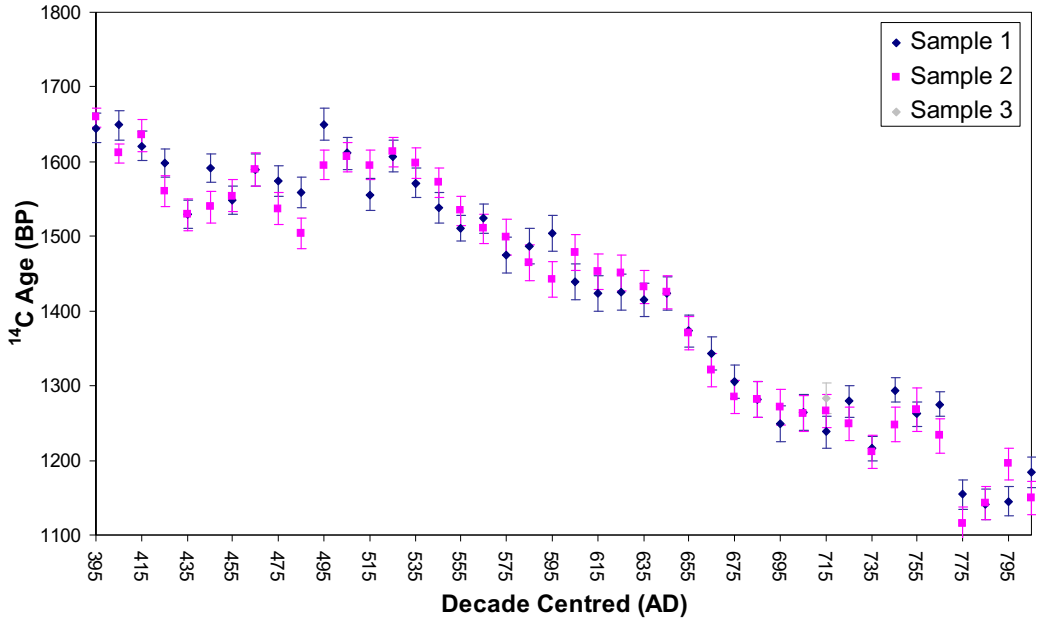


*Figure 12: Radiocarbon measurements from decadal samples of Irish oak (McCormac et al 2004; 2008)*

*Table 4: Decadal/bi-decadal averages of radiocarbon measurements from known-age wood samples, AD 395–805*

| | this report | | Stuiver *et al* (1998a) | | Pearson *et al* (1986) | |
|---|---|---|---|---|---|---|
| Decade Centred (AD) | Weighted Mean (BP) | error | Radiocarbon Age/ decadal average (BP) | error | Radiocarbon Age/ decadal average (BP) | error |
| 394.5 | 1655 | 11 | 1666 | 13 | | |
| 404.5 | 1622 | 11 | 1666 | 15 | 1645 | 17 |
| 414.5 | 1627 | 14 | 1639 | 16 | | |
| 424.5 | 1581 | 14 | 1618 | 13 | 1617 | 17 |
| 434.5 | 1530 | 14 | 1560 | 16 | | |
| 444.5 | 1568 | 14 | 1556 | 16 | 1571 | 17 |
| 454.5 | 1551 | 14 | 1580 | 17 | | |
| 464.5 | 1589 | 15 | 1578 | 17 | 1553 | 17 |
| 474.5 | 1556 | 15 | 1560 | 15 | | |
| 484.5 | 1532 | 15 | 1561 | 17 | 1588 | 17 |
| 494.5 | 1621 | 15 | 1561 | 13 | | |
| 504.5 | 1608 | 15 | 1580 | 15 | 1552 | 17 |
| 514.5 | 1576 | 15 | 1573 | 14 | | |
| 524.5 | 1610 | 15 | 1591 | 10 | 1534 | 18 |
| 534.5 | 1585 | 14 | 1559 | 16 | | |
| 544.5 | 1555 | 14 | 1497 | 11 | 1534 | 19 |
| 554.5 | 1521 | 13 | 1509 | 17 | | |
| 564.5 | 1517 | 14 | 1491 | 16 | 1487 | 18 |
| 574.5 | 1487 | 17 | 1497 | 17 | | |
| 584.5 | 1475 | 17 | 1475 | 16 | 1524 | 18 |
| 594.5 | 1473 | 17 | 1489 | 17 | | |
| 604.5 | 1459 | 17 | 1452 | 15 | 1463 | 18 |
| 614.5 | 1438 | 17 | 1442 | 32 | | |
| 624.5 | 1438 | 17 | 1444 | 16 | 1402 | 18 |
| 634.5 | 1424 | 16 | 1460 | 12 | | |
| 644.5 | 1425 | 16 | 1397 | 17 | 1408 | 12 |
| 654.5 | 1372 | 16 | 1371 | 16 | | |
| 664.5 | 1332 | 16 | 1342 | 17 | 1329 | 18 |
| 674.5 | 1295 | 16 | 1324 | 17 | | |
| 684.5 | 1281 | 17 | 1331 | 18 | 1279 | 18 |
| 694.5 | 1260 | 17 | 1262 | 16 | | |
| 704.5 | 1264 | 17 | 1294 | 15 | 1282 | 17 |
| 714.5 | 1264 | 12 | 1273 | 13 | | |
| 724.5 | 1264 | 16 | 1254 | 13 | 1246 | 12 |
| 734.5 | 1214 | 13 | 1248 | 10 | | |
| 744.5 | 1279 | 13 | 1263 | 11 | 1278 | 16 |
| 754.5 | 1263 | 14 | 1296 | 8 | | |
| 764.5 | 1261 | 13 | 1282 | 10 | 1247 | 16 |
| 774.5 | 1137 | 15 | 1247 | 11 | | |
| 784.5 | 1142 | 15 | 1168 | 10 | 1240 | 16 |
| 794.5 | 1168 | 15 | 1213 | 8 | | |
| 804.5 | 1169 | 15 | 1197 | 13 | | |

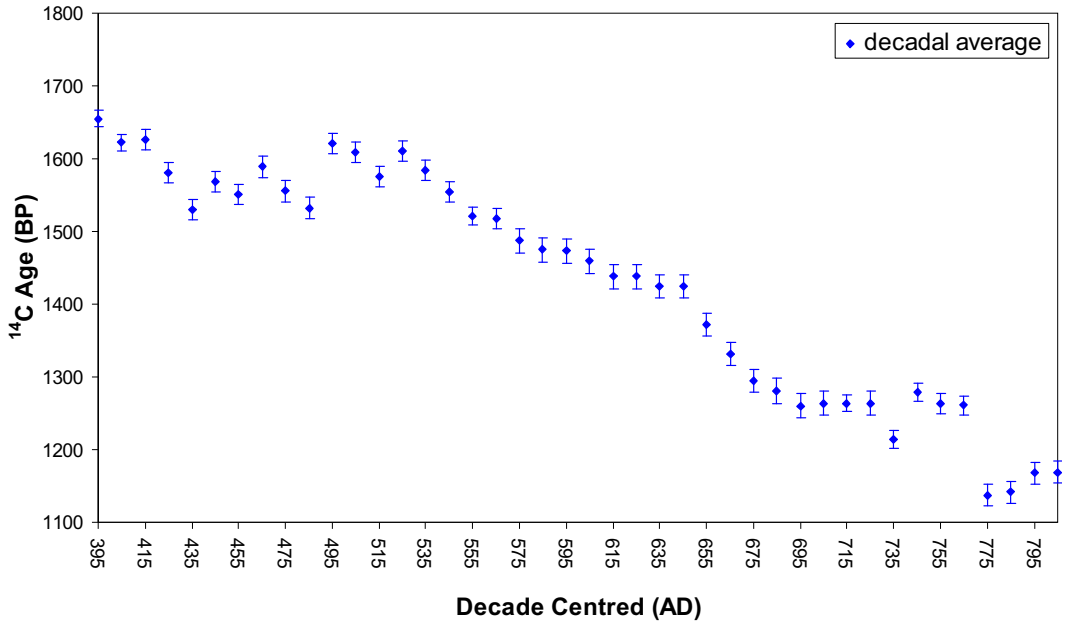


*Figure 13: Decadal means of radiocarbon measurements from decadal samples of Irish oak (McCormac et al 2004; 2008)*

Before this project two sets of measurements were already available on known-age wood for the Anglo-Saxon period. Bi-decadal samples of Irish oak (*Quercus* spp.) were measured in Belfast in the early 1980s (Pearson *et al* 1986) and decadal samples of sequoia (*Sequoia dendron*) and Douglas fir (*Pseudotsuga menziesii*) from the western coast of North America were measured by the University of Washington, Seattle (Stuiver and Becker 1986; corrected as described by Stuiver *et al* 1998a).

The decadal means of the data from this study are plotted with respect to Pearson *et al* (1986) in Figure 14[2]. To investigate differences between datasets, weighted means were calculated from the four decadal measurements on each bi-decade previously sampled. These twenty bi-decadal means were compared with the original Belfast measurements. In six of the twenty cases the pairs are statistically significantly different, with three pairs being different at more than 99% confidence. The mean difference between these datasets is –10.7±4.4 yr BP (Table 5).

*Table 5: Differences between the bi-decadal measurements on Irish oak (Pearson et al 1986) and the decadal measurements on Irish oak (Table 3)*

Number of comparisons = 20
Average difference = –9.7
Average standard deviation in difference = 19.9
Mean difference = –10.7 ± 4.4
Standard deviation (=square root of sample variance) = 33.7
k = Standard deviation/Average standard deviation in difference = 1.7

| Bi–decade centred (AD) | Difference (yr BP) | Standard Deviation |
|---|---|---|
| 409.5 | –20.8 | 19.1 |
| 429.5 | –61.8 | 19.7 |
| 449.5 | –11.6 | 19.7 |
| 469.5 | 18.8 | 20.0 |
| 489.5 | –10.7 | 19.9 |
| 509.5 | 40.4 | 19.9 |
| 529.5 | 62.9 | 20.6 |
| 549.5 | 2.3 | 21.2 |
| 569.5 | 17.8 | 21.0 |
| 589.5 | –50.0 | 21.6 |
| 609.5 | –15.0 | 21.6 |
| 629.5 | 28.1 | 21.4 |
| 649.5 | –9.8 | 16.3 |
| 669.5 | –15.5 | 21.1 |
| 689.5 | –8.5 | 21.6 |
| 709.5 | –18.2 | 20.6 |
| 729.5 | –11.5 | 15.6 |
| 749.5 | –6.3 | 18.7 |
| 769.5 | –40.4 | 18.8 |
| 789.5 | –85.3 | 19.1 |

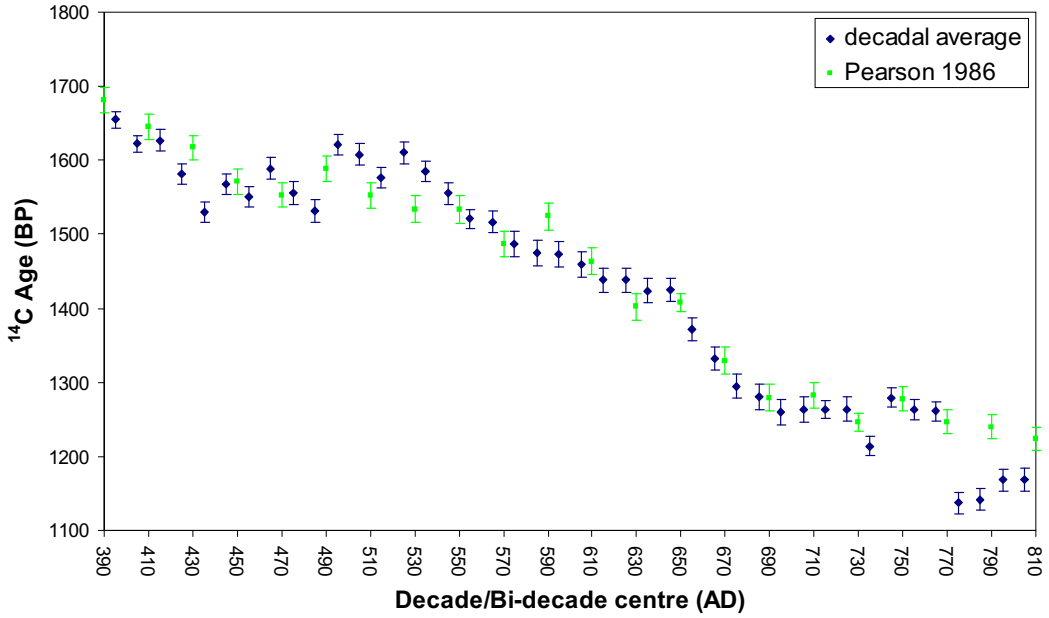


*Figure 14: Means of radiocarbon measurements from decadal samples of Irish oak (McCormac et al 2004; 2008) and bi-decadal samples of Irish oak (Pearson et al 1986)*

The new data are plotted alongside the measurements on North American conifers by the Seattle group (Stuiver and Becker 1986; corrected as described by Stuiver *et al* 1998a) in Figure 15. Eight decadal pairs are statistically significantly different in this case, with four pairs being different at more than 99% confidence. The mean difference between these datasets is –10.3±3.1 yr BP (Table 6).

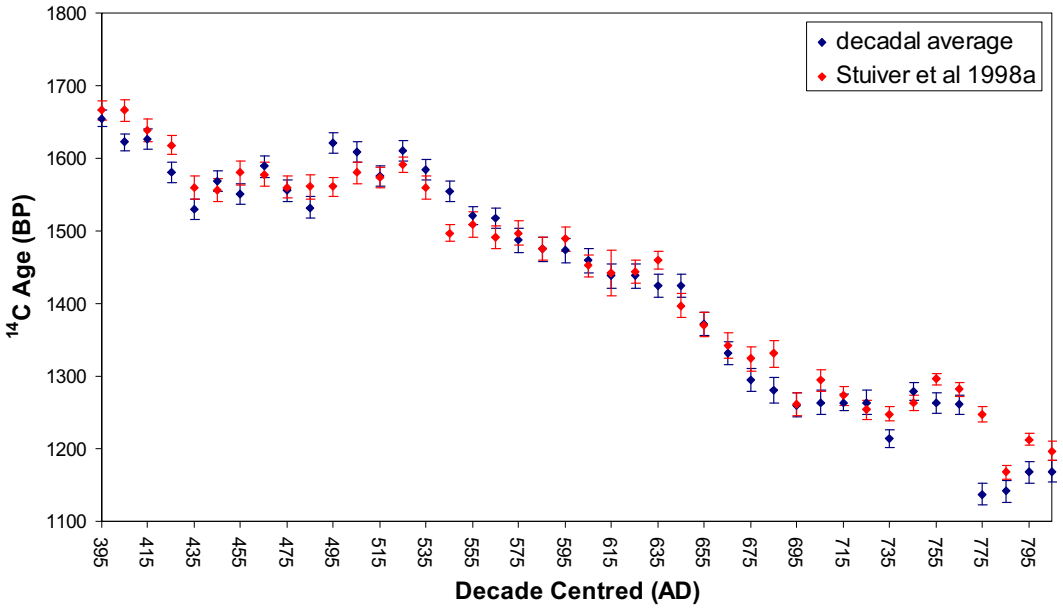


*Figure 15: Means of radiocarbon measurements from decadal samples of Irish oak (McCormac et al 2004; 2008) and decadal samples of American conifer (Stuiver and Becker 1986, corrected as reported in Stuiver et al 1998a)*

*Table 6: Differences between the decadal measurements on American conifers (Stuiver et al 1998a) and the decadal measurements on Irish oak (Table 3)*

Number of comparisons = 42
Average difference = –9.1
Average standard deviation in difference = 21.0
Mean difference = –10.3 ± 3.1
Standard deviation (=square root of sample variance) = 32.4
k = Standard deviation/Average standard deviation in difference = 1.6

| Decade Centred (AD) | Difference (yr BP) | Standard Deviation |
|---|---|---|
| 394.5 | –11.2 | 17.0 |
| 404.5 | –43.7 | 18.5 |
| 414.5 | –11.7 | 21.3 |
| 424.5 | –37.1 | 19.2 |
| 434.5 | –30.4 | 21.3 |
| 444.5 | 11.6 | 21.3 |
| 454.5 | –28.7 | 22.1 |
| 464.5 | 11.0 | 22.8 |
| 474.5 | –4.5 | 21.1 |
| 484.5 | –29.5 | 22.5 |
| 494.5 | 60.2 | 19.5 |
| 504.5 | 28.4 | 20.9 |

| 514.5 | 3.4 | 20.2 |
|---|---|---|
| Decade Centred (AD) | Difference (yr BP) | Standard Deviation |
| 524.5 | 19.1 | 17.6 |
| 534.5 | 25.5 | 21.3 |
| 544.5 | 58.0 | 17.9 |
| 554.5 | 12.2 | 21.2 |
| 564.5 | 26.0 | 21.3 |
| 574.5 | –10.0 | 24.0 |
| 584.5 | 0.0 | 23.3 |
| 594.5 | –16.0 | 24.0 |
| 604.5 | 6.5 | 22.7 |
| 614.5 | –4.5 | 36.2 |
| 624.5 | –6.0 | 23.3 |
| 634.5 | –36.5 | 19.7 |
| 644.5 | 27.5 | 23.1 |
| 654.5 | 1.0 | 22.3 |
| 664.5 | –10.0 | 23.1 |
| 674.5 | –29.0 | 23.1 |
| 684.5 | –50.0 | 24.8 |
| 694.5 | –2.0 | 23.3 |
| 704.5 | –30.5 | 22.7 |
| 714.5 | –9.3 | 17.9 |
| 724.5 | 10.0 | 20.3 |
| 734.5 | –33.7 | 16.3 |
| 744.5 | 16.0 | 17.1 |
| 754.5 | –32.6 | 16.1 |
| 764.5 | –20.7 | 16.5 |
| 774.5 | –110.2 | 18.4 |
| 784.5 | –26.1 | 17.9 |
| 794.5 | –45.4 | 16.8 |
| 804.5 | 28.4 | 19.7 |

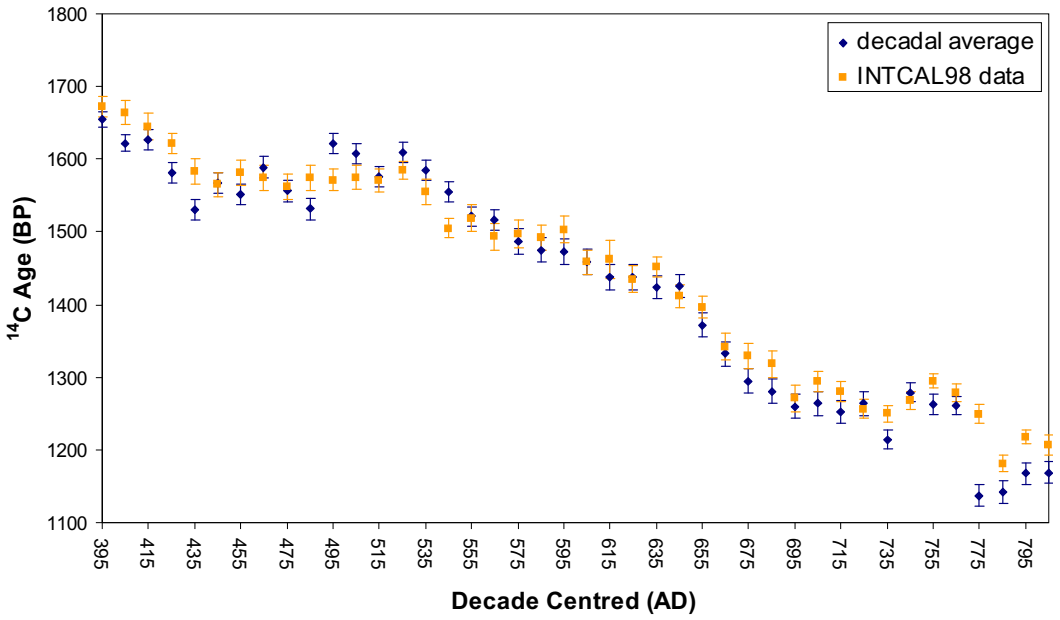


*Figure 16: Means of radiocarbon measurements from decadal samples of Irish oak (McCormac et al 2004; 2008 and IntCal98 (Stuiver et al 1998b)*

*Table 7: Differences between the decadal values for IntCal98 (Stuiver et al 1998b) and the decadal measurements on Irish oak (Table 3)*

Number of comparisons = 42
Average difference = –13.7
Average standard deviation in difference = 21.7
Mean difference = –14.6 ± 3.3
Standard deviation (=square root of sample variance) = 32.0
k = Standard deviation/Average standard deviation in difference = 1.5

| Decade Centred (AD) | Difference (yr BP) | Standard Deviation |
|---|---|---|
| 394.5 | –17.3 | 18.1 |
| 404.5 | –41.3 | 19.8 |
| 414.5 | –17.9 | 22.5 |
| 424.5 | –40.0 | 20.2 |
| 434.5 | –53.1 | 22.5 |
| 444.5 | 2.3 | 22.4 |
| 454.5 | –30.0 | 22.6 |
| 464.5 | 14.7 | 23.3 |
| 474.5 | –6.3 | 22.3 |
| 484.5 | –42.8 | 23.1 |
| 494.5 | 50.5 | 21.0 |
| 504.5 | 33.1 | 21.7 |
| 514.5 | 5.9 | 21.5 |
| 524.5 | 25.1 | 18.8 |

| Decade Centred(AD) | Difference (yr BP) | Standard Deviation |
|---|---|---|
| 534.5 | 29.5 | 22.6 |
| 544.5 | 50.4 | 19.4 |
| 554.5 | 2.2 | 22.4 |
| 564.5 | 23.8 | 22.7 |
| 574.5 | –10.3 | 25.1 |
| 584.5 | –17.1 | 24.2 |
| 594.5 | –30.4 | 24.8 |
| 604.5 | 0.7 | 23.9 |
| 614.5 | –24.8 | 30.7 |
| 624.5 | 2.8 | 24.4 |
| 634.5 | –28.6 | 20.8 |
| 644.5 | 13.4 | 22.1 |
| 654.5 | –23.6 | 21.5 |
| 664.5 | –9.7 | 24.0 |
| 674.5 | –34.3 | 24.0 |
| 684.5 | –36.7 | 25.3 |
| 694.5 | –10.5 | 24.7 |
| 704.5 | –30.7 | 22.2 |
| 714.5 | –17.4 | 18.3 |
| 724.5 | 7.9 | 20.6 |
| 734.5 | –36.1 | 16.8 |
| 744.5 | 10.9 | 17.9 |
| 754.5 | –32.0 | 17.4 |
| 764.5 | –16.7 | 17.9 |
| 774.5 | –112.4 | 19.6 |
| 784.5 | –39.1 | 18.6 |
| 794.5 | –50.5 | 17.5 |
| 804.5 | –38.4 | 20.6 |

Considering the decades in which the available calibration measurements are statistically significantly different, only in two cases are the new data incompatible with all three comparative datasets: Pearson *et al* (1986), Stuiver *et al* (1998a), and IntCal98 (Stuiver *et al* 1998b). These are for the decades centred on AD 775 and AD 795. The results of Pearson *et al* (1986) and Stuiver *et al* (1998a) are consistent for the former, but statistically significantly different for the latter. The new results show a rapid enrichment of $^{14}C$ between AD 765 and AD 775, which lies outside the 95% probability envelope for IntCal04 (Reimer *et al* 2004). Some of the decadal measurements made at the University of Washington (Stuiver *et al* 1998a) confirm atmospheric $^{14}C$ enrichment in this interval, although in a few instances these measurements lie closer to the original bi-decadal Belfast measurements. The large number of samples processed for this time period may suggest that there is difficulty in reaching a consensus value, or that there are regional differences in the interval of rapid enrichment. Further work is required to resolve this issue. The variability in the different calibration datasets vindicates the methodology of replicating sections of the calibration curve specifically for this project.

Figure 17 shows the radiocarbon age from Grave 91 at Edix Hill, Cambridgeshire (UB-4512; 1345±18 BP) calibrated using the raw measurements from the three calibration datasets currently available for the seventh century AD. The differences in the probability distributions of the calibrated dates are relatively subtle (less than twenty calendar years). However, because the rate of change of $^{14}C$ at this time produces precise calibrated dates, these differences can be proportionally significant. Variations of this magnitude are of considerable importance in the archaeological and historical interpretation of Anglo-Saxon chronological sequences.

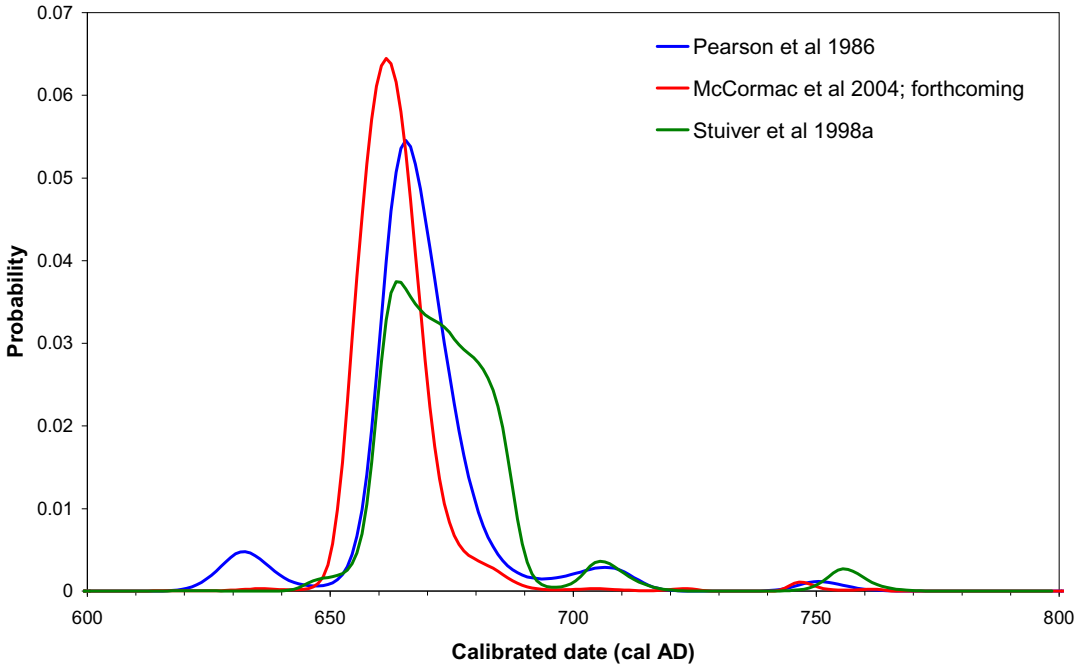


*Figure 17: Probability distributions for UB-4512 (1345±18 BP), calibrated by the probability method (Stuiver and Reimer 1993), using data from Pearson et al (1986), McCormac et al (2004), and Stuiver et al (1998b)*

## 5.3 The effect of pair separation

As noted above, to study the effect of sample combustion, a comparison was made of samples separated before combustion (decades AD 494.5–804.5, UB-4616–31, UB-4379–4410, and UB-6107–22) with those separated after combustion but before benzene synthesis (decades AD 394.5–484.5, UB-4933–52).

Table 8 shows the difference between replicate measurements on samples which were divided before combustion. The mean difference between these 34 pairs is –0.8± 5.2 yr BP. Table 9 shows the difference between replicate measurements on samples which were divided after combustion, but before benzene synthesis. The mean difference between these 10 pairs is 18.0 ± 8.7 yr BP. Although this may appear to show a

difference in results as a consequence of the sample preparation method, these differences are not statistically significant.

It should be noted that, because the samples were split after the production of $CO_2$, only one $\delta^{13}C$ measurement was made for each decadal pair in the range AD 394.5–484.5 (UB-4933–52).

***Table 8: Differences between paired measurements on known-age wood (Table 3) separated before combustion***

Number of comparisons = 34
Average difference = –1.1
Average standard deviation in difference = 30.7
Mean difference = –0.8 ± 5.2
Standard deviation (=square root of sample variance) = 30.2
k = Standard deviation/Average standard deviation in difference = 1.0

| Decade Centred (AD) | Difference (sample 1−sample 2) (yr BP) | Standard deviation |
|---|---|---|
| 494.5 | 55 | 29.0 |
| 504.5 | 5 | 29.0 |
| 514.5 | –39 | 29.0 |
| 524.5 | –6 | 29.0 |
| 534.5 | –27 | 28.3 |
| 544.5 | –34 | 28.3 |
| 554.5 | –23 | 25.5 |
| 564.5 | 14 | 28.3 |
| 574.5 | –24 | 33.9 |
| 584.5 | 22 | 33.9 |
| 594.5 | 62 | 33.9 |
| 604.5 | –39 | 33.9 |
| 614.5 | –29 | 33.9 |
| 624.5 | –26 | 33.9 |
| 634.5 | –17 | 31.1 |
| 644.5 | –1 | 31.1 |
| 654.5 | 2 | 31.1 |
| 664.5 | 22 | 31.1 |
| 674.5 | 20 | 31.1 |
| 684.5 | 0 | 33.9 |
| 694.5 | –22 | 33.9 |
| 704.5 | 1 | 33.9 |
| 714.5 (i) | –28 | 31.1 |
| 714.5 (ii) | –45 | 29.7 |
| 714.5 (iii) | –17 | 29.7 |
| 724.5 | 30 | 31.1 |
| 734.5 | 5 | 27.2 |

| | | |
|---|---|---|
| 744.5 | 46 | 28.0 |
| 754.5 | –6 | 33.1 |
| 764.5 | 42 | 28.0 |
| 774.5 | 38 | 29.7 |
| 784.5 | –2 | 29.7 |
| Decade Centred (AD) | Difference (sample 1−sample 2) (yr BP) | Standard deviation |
| 794.5 | -50 | 29.7 |
| 804.5 | 34 | 29.7 |

*Table 9: Differences between paired measurements on known-age wood (Table 3) separated after combustion, but before benzene synthesis*

Number of comparisons = 10
Average difference = 18.8
Average standard deviation in difference = 27.9
Mean difference = 18.0 ± 8.7
Standard deviation (=square root of sample variance) = 27.4
k = Standard deviation/Average standard deviation in difference = 1.0

| Decade Centred (AD) | Difference (sample 1-sample 2) (yr BP) | Standard deviation |
|---|---|---|
| 394.5 | –14 | 23.9 |
| 404.5 | 38 | 23.9 |
| 414.5 | –14 | 28.3 |
| 424.5 | 38 | 28.3 |
| 434.5 | 1 | 28.3 |
| 444.5 | 52 | 28.3 |
| 454.5 | –5 | 28.3 |
| 464.5 | 0 | 30.4 |
| 474.5 | 37 | 29.7 |
| 484.5 | 55 | 29.7 |

# 6 QUALITY ASSURANCE PROCEDURES

Strenuous efforts have been made to ensure the accuracy of the radiocarbon ages and their associated error estimates. In-house procedures involving daily monitoring of spectrometers, weekly monitoring of benzene sample weights, and benzene purity measurements are routinely performed (McCormac 1992; and see Section 2 above). Analyses are regularly carried out on quality control materials such as cellulose. Computerised quality control data are routinely recorded and monitored and age calculations are manually cross-checked.

As a further check to ensure that the methods and safeguards employed within the laboratory are effective, the Belfast laboratory is constantly involved in inter-laboratory comparisons. The laboratory contributed to the third and fourth International Radiocarbon Intercomparison (TIRI and FIRI), results of which are summarised briefly in Table 10. The application, importance, results and conclusions of these trials are detailed by Scott *et al* (1990; 1998) and Scott (2003). As discussed in Section 2, the internationally accepted modern reference material used at Belfast is Oxalic Acid II provided by the National Bureau of Standards (Mann 1983).

Intercomparison studies are useful as indicators of laboratory accuracy for a given level of precision. For the six TIRI samples reported by the Belfast laboratory, all results are statistically consistent with the consensus values (at 95% confidence; Table 10). The Belfast value for TIRI B, a sample of pine dated by tree-ring analysis to 3239–3200 BC, is also consistent with the measurements on the same sample undertaken as part of FIRI (D and F), and with the mean of the two bi-decadal measurements undertaken by Pearson *et al* (1986) on wood spanning these dates (Fig 18). Of the ten FIRI samples dated at Belfast, eight results are statistically consistent with the consensus values (at 95% confidence; Table 10). The reported age for FIRI H, a sample of oak dated by dendrochronology to 313–294 BC, is identical to the consensus value, although both are slightly older than the majority of the calibration data spanning this period (Fig 19). FIRI I was a sample of pine, dated by dendrochronology to 3299–3257 BC, and converted to cellulose in bulk at the Belfast laboratory. Following soxhlet extraction in petroleum ether, the sample was converted to holocellulose as described by Hoper *et al* (1998). The Belfast result on this material is significantly younger than the consensus value (at 95% confidence, but not 99% confidence), and younger than the calibration data available for samples from this period (Fig 20). The other sample whose result varied significantly from the consensus value in this intercomparison was FIRI C. It is uncertain why this result is younger than the consensus value especially since the TIRI F calcite gave an infinite age of >60590, however the FIRI A Kauri wood was at the younger end of the consensus range.

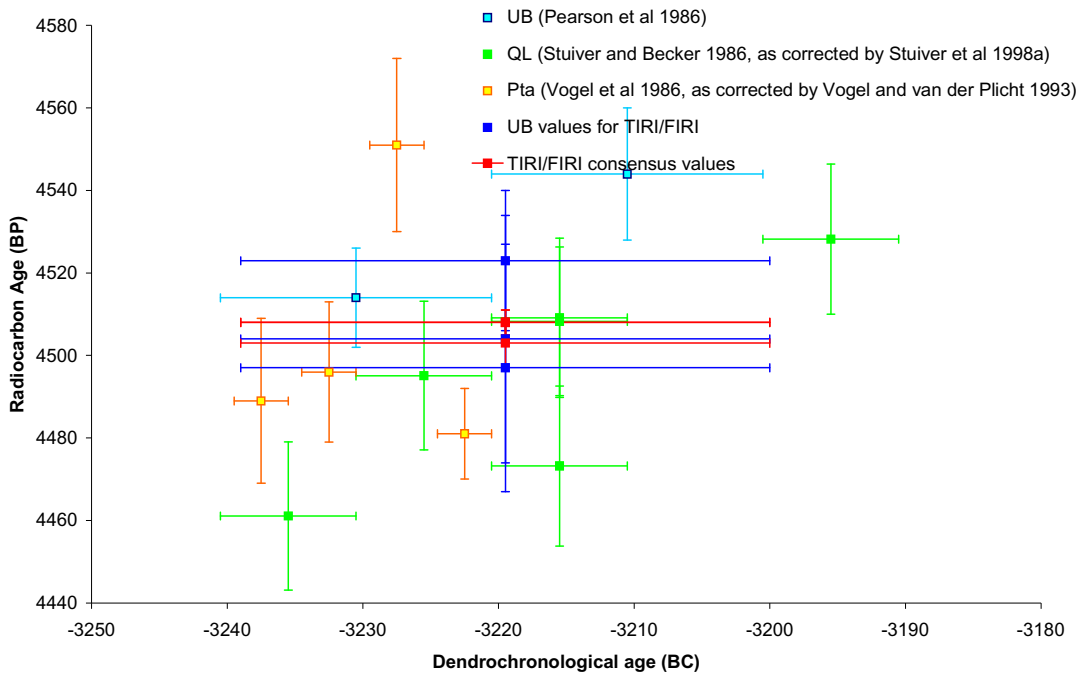


*Figure 18: Radiocarbon content of known-age wood samples covering the period of TIRI B and FIRI D and F (3239–3200 BC)*

*Table 10: Third (TIRI) and Fourth (FIRI) International Radiocarbon Intercomparison results from Queen's University Belfast*

| TIRI Sample Code and Description | Consensus Result (all labs) (pMC or BP) | QUB Radiometric Result (pMC or BP) |
|---|---|---|
| A – barley mash | 116.35±0.0084 pMC | 116.42 ± 0.20 pMC |
| B – known-age pine (3239–3200 BC) | 4503±6 BP | 4523 ± 17 BP |
| C – IAEA cellulose | 129.7±0.08 pMC | 129.56 ± 0.22 pMC |
| D – Hekla peat | 3810±7 BP | 3845 ± 22 BP |
| E – humic acid | 11129±0.08 BP | 11163 ± 36 BP |
| F – calcite | >46150 | >60590 |

| FIRI Sample Code and Description | Consensus Result (all labs) (pMC or years BP) | QUB Radiometric Result (pMC or Years BP ± 1σ) |
|---|---|---|
| A – Kauri wood | 0.15 ± 0.44 pMC | 0.417 ± 0.023 pMC |
| B – Kauri wood | 0.15 ±0.44 pMC | 0.267 ± 0.018 pMC |
| C – marine turbidite | 18173±10.5 BP | 17983 ± 50 BP |
| D – known-age pine (3239–3200 BC) | 4508±3 BP | 4497 ± 30 BP |
| E – humic acid | 11778±7 BP | 11741 ± 45 BP |
| F – known-age pine (3239–3200 BC) | 4508±3 BP | 4504 ± 30 BP |
| G – barley mash | 110.69±0.04 pMC | 110.87 ± 0.35 pMC |
| H – known-age oak (313–294 BC) | 2232±5 BP | 2232 ± 25 BP |
| I – UB cellulose (3299–3257 BC) | 4485±5 BP | 4401 ± 40 BP |
| J - barley mash | 110.69±0.04 pMC | 111.2 ± 0.35 pMC |

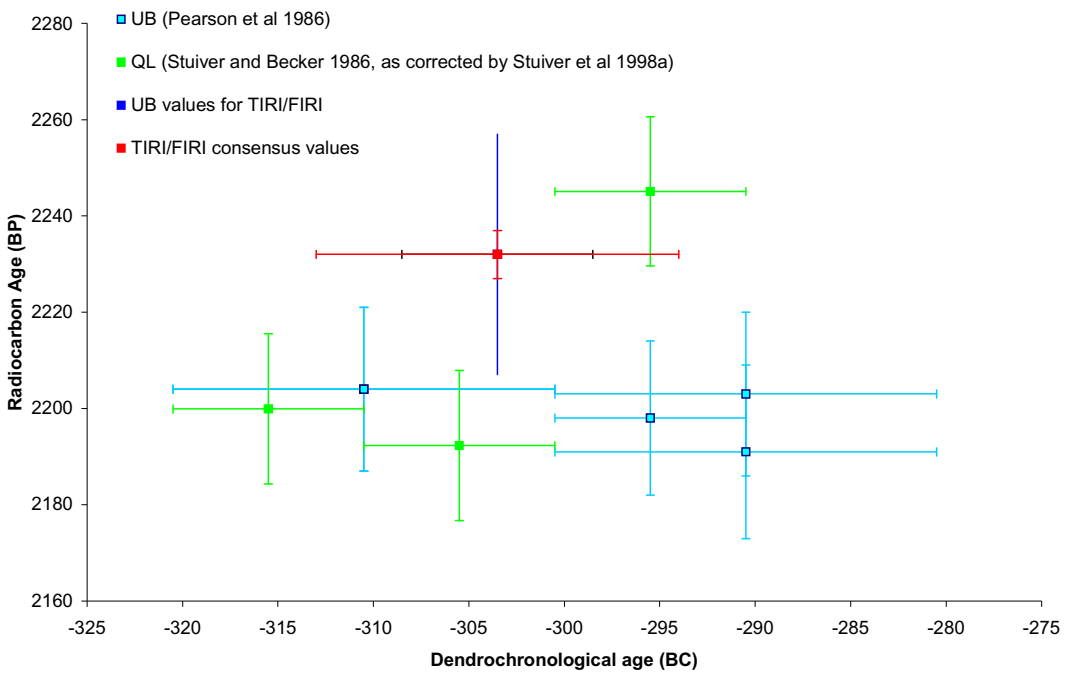


*Figure 19: Radiocarbon content of known-age wood samples covering the period of TIRI H (313–294 BC)*

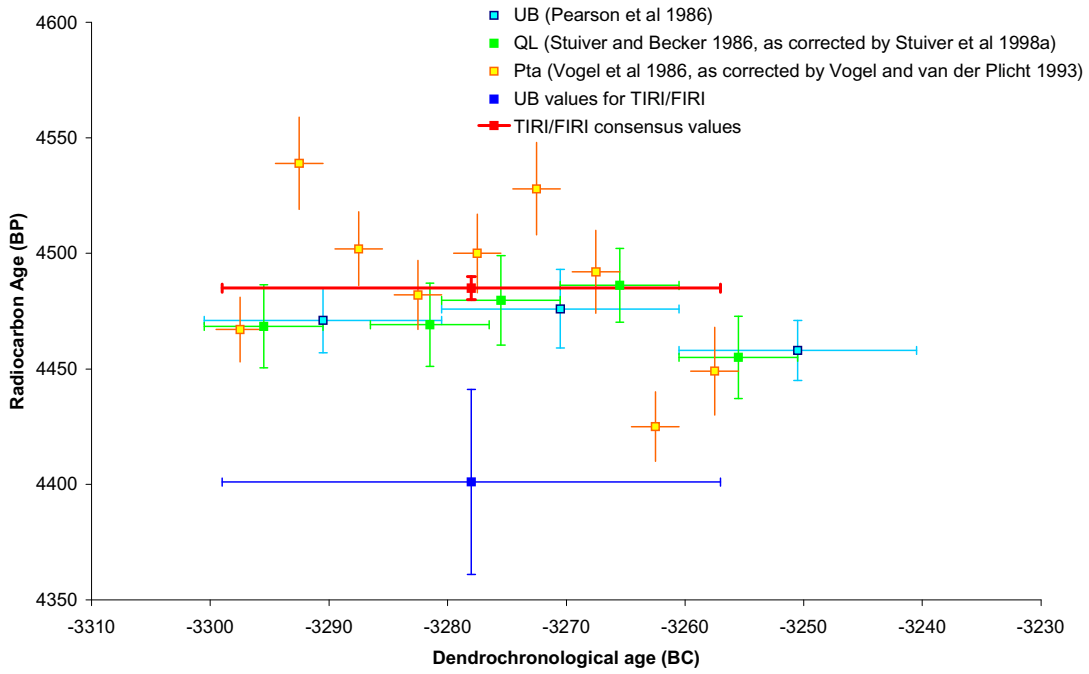


*Figure 20: Radiocarbon content of known-age wood samples covering the period of TIRI I (3299–3257 BC)*

# 7 BONE SAMPLES

The bone samples were processed in the radiocarbon laboratory as described in Section 2.

One sample, the primary burial from Gally Hills, appeared to have been treated with some form of consolidant between its excavation in 1972 and the collection of the sample in 2001. A radiocarbon determination on the right femur of this individual (UB-4727) was measured in December 2001, and produced a date older than that expected from the accompanying assemblage of grave goods. No conservation records or other information about the treatment of this skeleton was available in the site archive at Bourne Hall Museum (Jeremy Harte pers comm 2002). A second measurement was undertaken on the left femur of this individual in October 2003 (UB-4920). A sub-sample of this bone was tested at the Polymer Processing Research Centre at the Queen's University, Belfast (Millar 2003a). The sample was analysed by Fourier Transform Infra Red Spectroscopy (Hummel 1966) and the presence of Polyvinyl Acetate (PVA) was confirmed (Millar 2003a). This substance is used to consolidate archaeological material (UNESCO 1968; Ashley-Smith 1983), but is petroleum-derived and so of infinite radiocarbon age. If it is not completely removed from a sample, it dilutes the $^{14}C$ concentration in that sample and so makes its radiocarbon age anomalously old. As PVA is soluble in water, much of the original contamination would have been removed by the pre-treatment protocol for bone described in Section 2 and used for UB-4727. However, UB-4920 was also pre-treated using soxhlet extraction as outlined by Bruhn *et al* (2001). The sequence of solvents used in this case was: tetrahydrofuran (Boiling Point (B.P) 66°C), chloroform (B.P. 62°C), petroleum ether (B.P. 60°C), acetone (B.P. 56°C), methanol (B.P. 65°C) and water (B.P. 100 °C). Each solvent was applied for two cycles (a cycle being the time taken for the solvent to evaporate, condense, fill sample chamber, and siphon off into boiling flask prior to re-evaporation) at a temperature of 50–70°C for the solvents and 100 °C for the final water step. A further test for contamination was undertaken on the bone after soxhlet extraction, again using Fourier Transform Infra Red Spectroscopy (Millar 2003b). This confirmed the removal of a significant amount of the contaminant, although traces may have remained (Figs 21 and 22). Nonetheless, the sample was then processed for radiocarbon dating. UB-4920 is statistically significantly younger than the original measurement, UB-4727 (T'=8.0; T'(5%)=3.8; $\nu$=1; Ward and Wilson 1978). It is probable that UB-4920 is a more accurate estimate of the actual radiocarbon age of the primary burial at Gally Hills than UB-4727, although in the light of the contamination problems described here, the radiocarbon date of this individual must be interpreted with some caution.

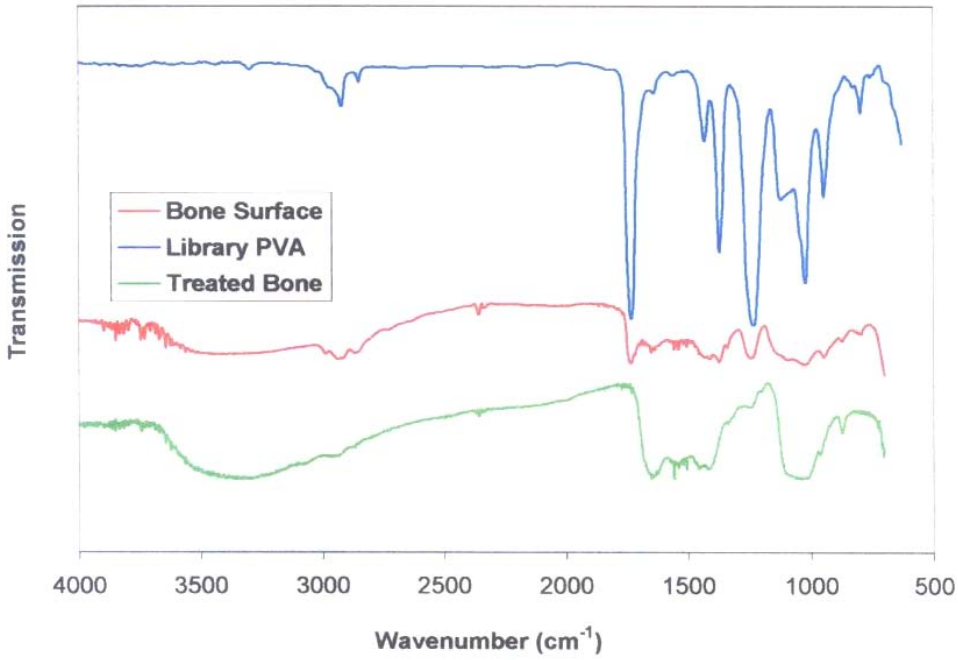


*Figure 21: Fourier Transform Infrared Spectroscopy (FTIR) scan of consolidated bone from Gally Hills, and the same bone after soxhlet extraction (Millar 2003b)*

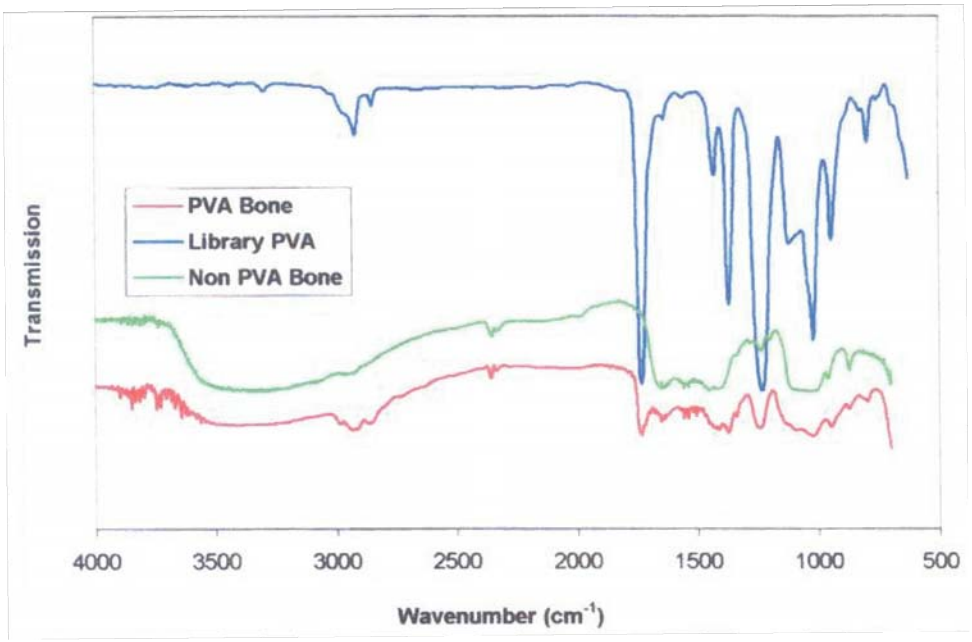


*Figure 22: Fourier Transform Infrared Spectroscopy (FTIR) scan of consolidated bone from Gally Hills, and an unconsolidated bone (Millar 2003c)*

As a further measure of quality control and to decrease the quoted error on a number of measurements, fourteen benzene samples (UB-4501–11, UB-4551–2, and UB-4554)

were vacuum distilled and recounted in a second liquid scintillation spectrometer, using the standards specific to the new machine. In all cases, the radiocarbon results were statistically consistent and have been combined to produce the radiocarbon ages quoted in Table 11.

*Table 11: Radiocarbon ages and $\delta^{13}C$ values[3] for bone samples dated as part of the Anglo-Saxon chronology project (in black), and relevant data from other projects (in blue)*

| Laboratory Number | Site & context | Radiocarbon Age (BP) | $\delta^{13}C$ (‰) |
|---|---|---|---|
| Female Graves | | | |
| UB-4077 | Buttermarket, grave 4275 | 1476±24 | –21.0±0.2 |
| UB-4501 | Lechlade: grave 14 | 1321±21 | –20.0±0.2 |
| UB-4502 | Lechlade: grave 138 | 1391±18 | –20.4±0.2 |
| UB-4503 | Lechlade: grave 148 | 1319±18 | –19.3±0.2 |
| UB-4504 | Lechlade: grave 179 | 1374±20 | –20.3±0.2 |
| UB-4506 | Lechlade: grave 172/2 | 1352±19 | –20.2±0.2 |
| UB-4507 | Lechlade: grave 187 | 1398±19 | –20.2±0.2 |
| UB-4511 | Edix Hill: grave 90 | 1507±19 | –20.3±0.2 |
| UB-4512 | Edix Hill: grave 91 | 1345±18 | –20.5±0.2 |
| UB-4549 | Marina Drive: grave C7 | 1328±19 | –20.6±0.2 |
| UB-4550 | Marina Drive: grave E1 | 1379±19 | –20.0±0.2 |
| UB-4551 | Marina Drive: grave E2 | 1325±19 | –20.3±0.2 |
| UB-4552 | Marina Drive: grave E3 | 1370±19 | –20.5±0.2 |
| UB-4553 | Marina Drive: grave D10 | 1326±21 | –20.8±0.2 |
| UB-4554 | Marina Drive: grave F2 | 1337±19 | –20.8±0.2 |
| UB-4705 | West Heslerton: grave 123 | 1502±21 | –20.6±0.5 |
| UB-4706 | West Heslerton: grave 118 | 1395±20 | –20.2±0.5 |
| UB-4707 | Edix Hill: grave 79 | 1528±21 | –20.6±0.5 |
| UB-4708 | Edix Hill: grave 83 | 1488±21 | –20.4±0.5 |
| UB-4709 | Edix Hill: grave 14 | 1495±21 | –20.7±0.5 |
| UB-4728 | Mill Hill: grave 64 | 1496±22 | –19.8±0.5 |
| UB-4729 | Mill Hill: grave 68 | 1503±22 | –19.7±0.5 |
| UB-4732 | Mill Hill: grave 94 | 1561±20 | –20.0±0.5 |
| UB-4733 | Mill Hill: grave 95 | 1606±20 | –20.1±0.5 |
| UB-4734 | Mill Hill: grave 105C | 1587±19 | –20.5±0.5 |
| UB-4735 | Berinsfield: grave 22 | 1567±19 | –20.1±0.5 |
| UB-4739 | Berinsfield: grave 134/1 | 1561±21 | –20.5±0.5 |
| UB-4835 | Appledown Compton, grave 134 | 1503±16 | –20.5±0.5 |
| UB-4836 | Westgarth Gardens, grave 27 | 1560±20 | –20.1±0.5 |
| UB-4883 | Melbourne: SK1038, SG95 | 1416±20 | –20.4±0.5 |
| UB-4885 | Melbourne, InL1189 SG78 (stratigraphically later than MelSG077) | 1479±20 | –20.3±0.5 |
| UB-4887 | Melbourne: SK 1229 SG82 | 1421±20 | –20.6±0.5 |
| UB-4888 | Melbourne: SK1271 SG89 | 1536±19 | –20.6±0.5 |
| Laboratory Number | Site & context | Radiocarbon Age (BP) | $\delta^{13}C$ (‰) |
| Female Graves | | | |

| | | | |
|---|---|---|---|
| UB-4889 | Melbourne: SK1293, SG69 | 1459±19 | –20.4±0.5 |
| UB-4890 | Melbourne: SK1307 SG75 | 1548±20 | –20.6±0.5 |
| UB-4910 | Bloodmoor Hill: grave 22 | 1365±15 | –20.5±0.5 |
| Laboratory Number | Site & context | Radiocarbon Age (BP) | $\delta^{13}C$ (‰) |
| UB-4959 | Dover Buckland: grave 391A | 1420±20 | –20.5±0.5 |
| UB-4963 | St Peter's Tip: grave 208 | 1432±21 | –20.1±0.5 |
| UB-4964 | Coddenham: grave 30 | 1417±16 | –20.7±0.5 |
| UB-4965 | Appledown Compton: grave 117 | 1475±21 | –20.9±0.5 |
| UB-4975 | Aston Clinton: grave 12 | 1517±19 | –21.0±0.5 |
| UB-4984 | Lechlade: grave 18 | 1507±20 | –20.7±0.5 |
| UB-5208 | Appledown Compton: grave 107 | 1481±20 | –20.6±0.5 |
| UB-6032 | St Peter's Tip: grave 73 | 1422±17 | –21.2±0.5 |
| UB-6033 | West Heslerton: grave 113 | 1497±17 | –21.1±0.5 |
| UB-6034 | Castledyke South: grave 120 | 1502±17 | –21.2±0.5 |
| UB-6035 | Castledyke South: grave 96 | 1517±15 | –21.6±0.5 |
| UB-6036 | Castledyke South: grave 13 | 1421±17 | –21.2±0.5 |
| UB-6037 | Castledyke South: grave 134 | 1544±14 | –20.9±0.5 |
| UB-6038 | Castledyke South: grave 183 | 1449±14 | –21.3±0.5 |
| UB-6040 | Castledyke South: grave 53 | 1535±15 | –21.4±0.5 |
| UB-6041 | Castledyke South: grave 182 (stratigraphically earlier than UB-6038) | 1515±15 | –20.8±0.5 |
| UB-6042 | Castledyke South: grave 88 | 1323±13 | –20.6±0.5 |
| UB-6472 | Dover Buckland: grave 222 | 1550±19 | –20.1±0.5 |
| UB-6473 | Dover Buckland: grave 250 | 1572±22 | –20.1±0.5 |
| UB-6476 | Dover Buckland: grave 339 | 1592±17 | –20.0±0.5 |
| HAR-8243 | West Heslerton: grave 177 | 1610±40 | –20.3 |
| Male Graves | | | |
| BM-640 | Sutton Hoo: grave 1 (beeswax) | 1427±45 | –25.0 (assumed) |
| BM-688 | Sutton Hoo: grave 1 (wood) | 1256±45 | –26.6 |
| UB-4074 | Buttermarket: grave 2297 | 1419±23 | –20.6±0.2 |
| UB-4422 | Sutton Hoo: grave 17 (man) | 1534±35 | –20.0±0.2 |
| UB-4423 | Sutton Hoo: grave 17 (horse) | 1420±28 | –22.9±0.2 |
| UB-4505 | Lechlade: grave 172/1 | 1383±19 | –20.2±0.2 |
| UB-4508 | Edix Hill: grave 12 | 1488±19 | –20.2±0.2 |
| UB-4509 | Edix Hill: grave 33 | 1521±18 | –20.1±0.2 |
| UB-4510 | Edix Hill: grave 48 | 1479±19 | –20.2±0.2 |
| UB-4922 | replicate of UB-4510 | 1508±19 | –20.9±0.5 |
| UB-4682 | Westgarth Gardens: grave 66 | 1491±18 | –20.2±0.2 |
| UB-4727 | Gally Hills: primary burial | 1487±16 | –20.6±0.5 |
| UB-4920 | replicate of UB-4727 | 1419±18 | –20.5±0.5 |
| UB-4730 | Mill Hill: grave 79 | 1542±18 | –19.4±0.5 |
| UB-4731 | Mill Hill: grave 93 | 1508±18 | –20.1±0.5 |
| UB-4736 | Berinsfield: grave 28 | 1526±21 | –20.2±0.5 |
| UB-4882 | Melbourne: SK1187 SG80 (stratigraphically later than MelSG079) | 1378±20 | –20.4±0.5 |
| UB-4884 | Melbourne: SK1188 SG79 (stratigraphically later than MelSG078) | 1404±19 | –20.6±0.5 |

| | | | |
|---|---|---|---|
| UB-4886 | Melbourne: SK1204 SG77 | 1458±20 | –20.3±0.5 |
| UB-6345 | replicate of UB-4886 | 1516±23 | –19.8±0.5 |
| UB-4921 | Mill Hill: grave 81 | 1560±16 | –20.6±0.5 |
| UB-4923 | Edix Hill: grave 7 | 1572±20 | –20.6±0.5 |
| UB-4924 | St Peter's Tip: grave 113 | 1261±16 | –20.0±0.5 |
| UB-6534 | replicate of UB-4924 | 1311±18 | –19.7±0.5 |
| Laboratory Number | Site & context | Radiocarbon Age (BP) | $\delta^{13}C$ (‰) |
| UB-4925 | St Peter's Tip: grave 68 | 1466±16 | –19.7±0.5 |
| UB-4926 | St Peter's Tip: grave 212 | 1537±18 | –20.3±0.5 |
| UB-4927 | St Peter's Tip: grave 263 | 1471±18 | –20.0±0.5 |
| UB-4928 | St Peter's Tip: grave 250 | 1458±18 | –20.4±0.5 |
| UB-4929 | St Peter's Tip: grave 194 | 1485±18 | –20.3±0.5 |
| UB-4930 | St Peter's Tip: grave 42 | 1414±19 | –19.7±0.5 |
| UB-6346 | replicate of UB-4930 | 1435±16 | –19.3±0.5 |
| UB-4931 | St Peter's Tip: grave 318 | 1498±21 | –20.3±0.5 |
| UB-4958 | Dover Buckland: grave 375 | 1493±18 | –20.0±0.5 |
| UB-4961 | St Peter's Tip: grave 8 | 1447±17 | –19.8±0.5 |
| UB-4962 | St Peter's Tip: grave 196 | 1445±16 | –20.2±0.5 |
| UB-4976 | Ford, Laverstock | 1464±16 | –20.6±0.5 |
| UB-4981 | Lechlade: grave 183 | 1469±18 | –20.6±0.5 |
| UB-4982 | Lechlade: grave 155 | 1361±17 | –21.0±0.5 |
| UB-4683 | Lechlade: grave 40 | 1362±17 | –20.1±0.2 |
| UB-4985 | Westgarth Gardens: grave 11 | 1528±18 | –21.1±0.5 |
| UB-6039 | Castledyke South: grave 94 | 1412±14 | –20.8±0.5 |
| UB-6347 | Lakenheath: warrior 4222 | 1640±20 | –20.1±0.5 |
| UB-6348 | Lakenheath: horse 4206 | 1611±20 | –22.9±0.5 |
| UB-6474 | Dover Buckland: grave 264 | 1528±17 | –20.0±0.5 |
| UB-6475 | Dover Buckland: grave 323 | 1491±18 | –20.1±0.5 |
| UB-6477 | Dover Buckland: grave 414 | 1570±20 | –20.1±0.5 |
| UB-6478 | St Peter's Tip: grave 360 | 1414±16 | –20.4±0.5 |
| UB-6479 | Mill Hill: grave 40 | 1555±22 | –19.8±0.5 |
| Comparanda (men) | | | |
| UB-4039 | Buttermarket: grave 3871 | 1441±20 | –20.9±0.2 |
| UB-4642 | West Heslerton: grave 72 | 1487±19 | –19.9±0.2 |
| UB-4880 | Lundenwic (BOB91) | 1318±18 | –20.4±0.5 |
| HAR-8242 | West Heslerton: grave 176 | 1510±40 | –20.6 |
| Comparanda (women) | | | |
| UB-4042 | Buttermarket: grave 1674 | 1407±20 | –21.3±0.2 |
| UB-4044 | Buttermarket: grave 4152 | 1413±21 | –20.3±0.2 |
| OxA-6792 | replicate of UB-4044 | 1200±40 | –19.5 |
| OxA-6793 | replicate of UB-4044 | 1355±45 | –19.7 |
| OxA-7859 | replicate of UB-4044 | 1365±40 | –19.5 |
| OxA-7860 | replicate of UB-4044 | 1415±40 | –19.6 |
| UB-4960 | Dover Buckland: grave 391B | 1611±18 | –20.3±0.5 |

# 8 REPLICATION

The unknown age bone samples dated for this project were analysed between 1999 and 2006. As discussed in Section 5, 42 pairs of radiocarbon measurements on decadal samples of known-age wood were also undertaken as part of this project. All pairs are statistically consistent (Ward and Wilson 1978). These wood samples were dated in 1999, 2001, and 2003–4, and so demonstrate the reproducibility of the results from the laboratory over an extended period of time.

The sample size required for high-precision radiocarbon dating inevitably limited the number of replicate measurements that could be undertaken on samples of human bone from this project. In five cases, however, replicate samples were dated from bones of the same individual (Table 11). Of these, the two measurements on the primary burial from Gally Hills (UB-4727 and UB-4920) are not statistically consistent, almost certainly because of the difficulty of removing the chemical contamination discussed above. The two results from Edix Hill, grave 48 (UB-4510 and UB-4922) are statistically consistent ($T'=1.2$; $T'(5\%)=3.8$; $\nu=1$; Ward and Wilson 1978). Replicate measurements on SG77 from Melbourne Water Lane (UB-4886 and UB-6345) are also consistent ($T'=3.6$; $T'(5\%)=3.8$; $\nu=1$); as are the two determinations on St Peter's Tip, grave 42 (UB-4930 and UB-6346; $T'=0.7$; $T'(5\%)=3.8$; $\nu=1$). Finally, the two measurements from St Peter's Tip, grave 113 (UB-4924 and UB-6534) are not statistically consistent ($T'=4.3$; $T'(5\%)=3.8$; $\nu=1$). Although these results are statistically different at 95% confidence, they are consistent at 99% confidence. A further replicate measurement, on the skeleton from Appledown Compton, grave 117 (UB-4965), failed in laboratory processing. The consistency of these replicate pairs on bone samples confirms the reproducibility of the quoted ages over the duration of the project.

To test for potential dietary offsets in radiocarbon dates obtained from human bone, a pair of measurements was made on a horse and a man buried together in grave 104 at Lakenheath, Suffolk. These results are statistically consistent (UB-6347–8; $T'=1.1$; $T'(5\%)=3.8$; $=1$), suggesting that there was no significant marine or freshwater offset in the diet of the dated human being.

Full details of all the radiocarbon results from the bone samples dated as part of this project are provided in Table 11 (in black)[4]. Details of further stable isotope and amino-acid analyses on these samples are provided in Beavan *et al* (2011).

# 9 ARCHAEOLOGICAL AND NUMISMATIC SEQUENCES

Ten samples come from graves whose relative dating is known by archaeological stratigraphy. This information can be used as an independent check on the accuracy of the radiocarbon dating of these skeletons.

Grave 90 from Edix Hill (UB-4511) was overlain by grave 91 (UB-4512) (Malim and Hines 1998, 80–1), and indeed the two measurements are in good agreement with this relative order of burial (Fig 23).

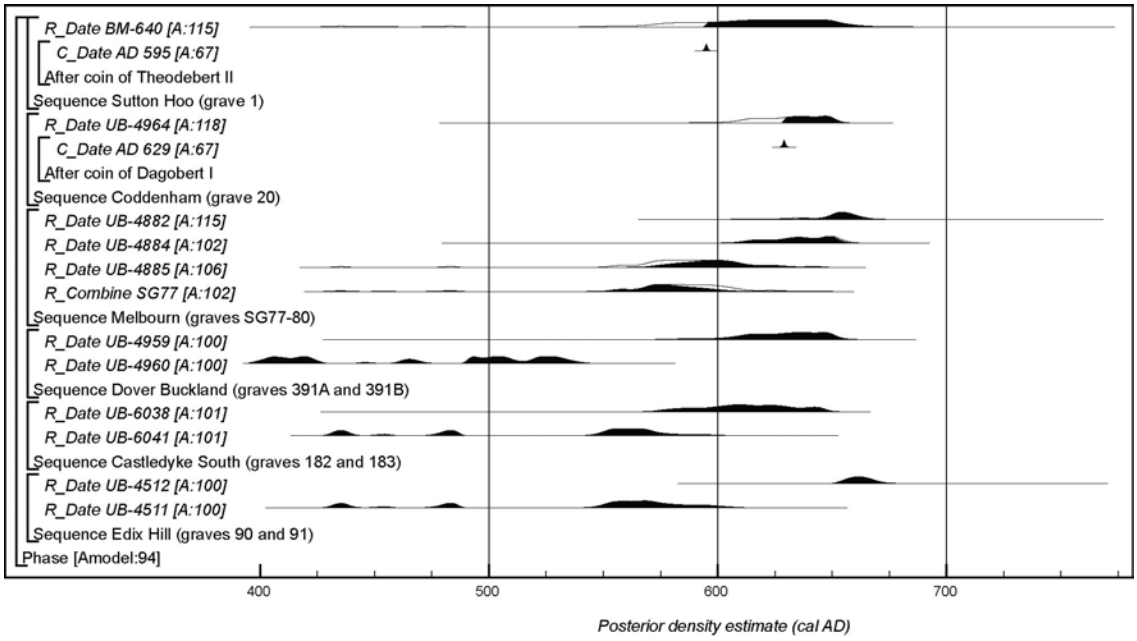


*Figure 23: Probability distributions of dates from stratigraphically related burials, and from burials containing coins that can be assigned to documented Merovingian kings. Each distribution represents the relative probability that an event occurs at a particular time. For each of the dates two distributions have been plotted: one in outline, which is the result of simple radiocarbon calibration (McCormac et al 2004; 2008), and a solid one, based on the chronological model used. The large square brackets down the left-hand side along with the OxCal keywords define the overall models exactly*

Grave 182 from Castledyke South (UB-6041) was cut by grave 183 (UB-6038) (Drinkall and Foreman 1998, 89 and fig 44), and again the two measurements are in good agreement with this relative order of burial (Fig 23).

Grave 391B from the cemetery at Dover Buckland (UB-4960) was cut by grave 391A (BU-4959) (Parfitt pers comm), and again the two measurements are in good agreement with this relative order of burial (Fig 23).

A sequence of four burials has been dated from Melbourne, Water Lane (Duncan *et al* 2003, 92–4). Two statistically consistent determinations are available from a skeleton buried in the earliest grave, SG77 (UB-4886 and UB-6345). This was cut by grave SG78 which contained the skeleton dated by UB-4885. Grave SG78 was itself cut by grave SG79, which also contained an intact inhumation (UB-4884). Grave SG79 was in turn cut by another grave, SG80 (UB-4882). A chronological model which incorporates this stratigraphic information with the calibrated radiocarbon dates from these burials has good agreement (Fig 23).

Finally, two of the Anglo-Saxon skeletons which have been radiocarbon dated and are included in this project were buried with coins that can be assigned to Merovingian kings who appear in historical sources. Grave 20 at Coddenham, Suffolk (UB-4964) includes a coin of Dagobert I, King of the Merovingian Franks (reigned AD 629–39), and so must date after AD 629, the earliest possible minting date for the coin. Similarly, the coin of Theodebert II, King of Austrasia (reigned AD 595–612) found in the purse which accompanied the ship burial in mound 1 at Sutton Hoo (Bruce-Mitford 1975, 609), provides a *terminus post quem* of AD 595 for the radiocarbon date from that burial undertaken by the British Museum laboratory in the late 1960s (BM-640). In both cases, the radiocarbon dates from these burials are fully compatible with the historically-attested coin dates (Fig 23).

## 10 $\delta^{13}$C MEASUREMENTS

For all samples dated at Belfast $\delta^{13}$C values are measured for the purposes of age calculation (Stuiver and Polach 1977). As described in Section 2.3, the carbon dioxide produced for dating by the positive pressure flow-through combustion system was sub-sampled for stable isotope measurement. The fractionation reported in these results might derive from the combustion process in addition to the natural isotopic composition of the dated material. This measurement reflects the true fractionation in the dated sample and so is appropriate for age calculation.

As part of measures to assess the accuracy of the radiocarbon dates for the Anglo-Saxon burials, the natural isotopic composition of the bone samples was of interest, however. In combination, the $\delta^{13}$C and $\delta^{15}$N values of such bones may be used as an indicator of the proportion of marine protein in an individual's diet in areas such as the British Isles where there were no C4 plants (Mays 1998, fig 9.2). As the marine reservoir is significantly older than the terrestrial biosphere (Hughen *et al* 2004), a diet rich in marine protein may result in a bone with depleted levels of radiocarbon and an older apparent age. Protocols for calibrating such radiocarbon ages accurately, by estimating the proportion of marine and terrestrial components in the diet, are currently inexact (Arneborg *et al* 1999; Bayliss *et al* 2004). In the Anglo-Saxon period, however, a significant proportion of marine protein would not be expected in the diets of most individuals (Privat *et al* 2002), as this pre-dates intensive marine fishing in England (Barrett *et al* 2004a–b). There could have been some marine input into the diets of some dated individuals, however, and so stable

isotope measurements appropriate for inferring past diets were also undertaken as part of this study to check for any ages which might be misleading.

For this reason, sub-samples of the dated bones were sent to the National Isotope Centre, GNS Science, New Zealand. Here they were chemically pre-treated to bone gelatin at the Rafter Radiocarbon Laboratory as described by Beavan-Athfield *et al* (2001). The gelatin was analysed at Isotrace New Zealand for nitrogen and carbon ($\delta^{15}N$, $\delta^{13}C$, % N and C) using elemental analyser isotope ratio mass spectrometry (EA-IRMS). Full technical details of these analyses are provided in Beavan *et al* (2011).

To investigate the magnitude of fractionation introduced by the positive pressure flow-through combustion system used for preparing dating samples at Belfast, $\delta^{13}C$ values were measured by both Belfast and Isotrace New Zealand on sub-samples of the bone protein extracted at Belfast for dating. These replicate pairs of results are listed in Table 12. Figure 24 shows the offset between the results on each sample against the date when the sample was converted to benzene following combustion and stable isotope analysis at Belfast. Before October 2001 the results are in good agreement, with a mean difference of 0.07±0.54‰. This negligible difference suggests that minimal additional fractionation is induced in the flow-through combustion system. Bone samples, although more difficult to combust, do not appear to fractionate more during combustion than wood samples, since the mean difference for 30 pairs of wood samples is 0.57±0.22‰ (Table 13), consistent with that observed for bone samples processed before October 2001. After this date, however, the results on bone protein from Belfast become significantly depleted compared to those made in New Zealand (with a mean difference of -1.87±1.46‰; Fig 24).

***Table 12: $\delta^{13}C$ values on the bone protein extracted for radiocarbon dating at the Queen's University, Belfast, measured by (a) the Belfast Radiocarbon Laboratory and (b) Rafter Radiocarbon (samples included in this project are in black)***

| Laboratory Number | Belfast | | Rafter | | Date converted to $C_6H_6$ |
|---|---|---|---|---|---|
| | $\delta^{13}C$ (‰) | error (‰) | $\delta^{13}C$ (‰) | error (‰) | |
| UB-4306 | –18.6 | 0.2 | –18.7 | 0.1 | 01/07/1998 |
| UB-4307 | –18.6 | 0.2 | –18.8 | 0.1 | 02/07/1998 |
| UB-4308 | –18.3 | 0.2 | –18.4 | 0.1 | 03/07/1998 |
| UB-4309 | –18.3 | 0.2 | –18.6 | 0.1 | 06/07/1998 |
| UB-4310 | –20.3 | 0.2 | –19.8 | 0.1 | 08/07/1998 |
| UB-4549 | –20.6 | 0.2 | –21.1 | 0.1 | 28/03/2000 |
| UB-4550 | –20.0 | 0.2 | –21.1 | 0.1 | 29/03/2000 |
| UB-4551 | –20.3 | 0.2 | –20.8 | 0.1 | 27/03/2000 |
| UB-4552 | –20.5 | 0.2 | –22.1 | 0.1 | 31/03/2000 |
| UB-4553 | –20.8 | 0.2 | –21.1 | 0.1 | 04/04/2000 |
| UB-4554 | –20.8 | 0.2 | –21.5 | 0.1 | 05/04/2000 |
| UB-4641 | –20.0 | 0.2 | –20.2 | 0.1 | 01/05/2001 |
| UB-4642 | –19.9 | 0.2 | –19.8 | 0.1 | 02/05/2001 |

| UB-4643 | –20.3 | 0.2 | –20.4 | 0.1 | 03/05/2001 |
|---|---|---|---|---|---|
| Laboratory Number | Belfast | | Rafter | | Date converted to $C_6H_6$ |
| | $\delta^{13}C$ (‰) | error (‰) | $\delta^{13}C$ (‰) | error (‰) | |
| UB-4644 | –21.3 | 0.2 | –19.9 | 0.1 | 09/05/2001 |
| UB-4645 | –19.9 | 0.2 | –20.4 | 0.1 | 11/05/2001 |
| UB-4646 | –20.2 | 0.2 | –20.1 | 0.1 | 14/05/2001 |
| UB-4647 | –18.8 | 0.2 | –19.1 | 0.1 | 16/05/2001 |
| UB-4648 | –19.9 | 0.2 | –19.8 | 0.1 | 17/05/2001 |
| UB-4649 | –20.1 | 0.2 | –20.0 | 0.1 | 18/05/2001 |
| UB-4650 | –19.9 | 0.2 | –20.1 | 0.1 | 23/05/2001 |
| UB-4651 | –19.4 | 0.2 | –19.2 | 0.1 | 24/05/2001 |
| UB-4652 | –19.4 | 0.2 | –20.3 | 0.1 | 25/05/2001 |
| UB-4653 | –20.0 | 0.2 | –20.0 | 0.1 | 29/05/2001 |
| UB-4654 | –19.7 | 0.2 | –19.9 | 0.1 | 01/06/2001 |
| UB-4655 | –19.8 | 0.2 | –19.4 | 0.1 | 07/06/2001 |
| UB-4656 | –20.0 | 0.2 | –20.0 | 0.1 | 08/06/2001 |
| UB-4657 | –19.5 | 0.2 | –19.0 | 0.1 | 22/06/2001 |
| UB-4658 | –19.5 | 0.2 | –19.3 | 0.1 | 26/06/2001 |
| UB-4659 | –19.4 | 0.2 | –19.0 | 0.1 | 27/06/2001 |
| UB-4660 | –19.5 | 0.2 | –19.5 | 0.1 | 28/06/2001 |
| UB-4661 | –20.4 | 0.2 | –19.8 | 0.1 | 29/06/2001 |
| UB-4662 | –20.0 | 0.2 | –19.7 | 0.1 | 03/07/2001 |
| UB-4663 | –19.2 | 0.2 | –18.8 | 0.1 | 06/07/2001 |
| UB-4705 | –20.9 | 0.2 | –20.3 | 0.1 | 24/10/2001 |
| UB-4706 | –21.1 | 0.2 | –20.4 | 0.1 | 25/10/2001 |
| UB-4707 | –19.7 | 0.2 | –20.2 | 0.1 | 26/10/2001 |
| UB-4708 | –21.3 | 0.2 | –20.5 | 0.1 | 29/10/2001 |
| UB-4709 | –21.3 | 0.2 | –20.4 | 0.1 | 01/11/2001 |
| UB-4719 | –20.8 | 0.2 | –19.7 | 0.1 | 05/11/2001 |
| UB-4720 | –20.5 | 0.2 | –19.4 | 0.1 | 06/11/2001 |
| UB-4727 | –21.3 | 0.2 | –20.0 | 0.1 | 27/11/2001 |
| UB-4728 | –22.1 | 0.2 | –19.9 | 0.1 | 28/11/2001 |
| UB-4729 | –21.7 | 0.2 | –19.7 | 0.1 | 03/12/2001 |
| UB-4730 | –20.5 | 0.2 | –19.6 | 0.1 | 04/12/2001 |
| UB-4731 | –23.1 | 0.2 | –19.4 | 0.1 | 05/12/2001 |
| UB-4732 | –20.6 | 0.2 | –19.7 | 0.1 | 25/01/2002 |
| UB-4733 | –21.5 | 0.2 | –19.7 | 0.1 | 28/01/2002 |
| UB-4734 | –21.2 | 0.2 | –19.9 | 0.1 | 29/01/2002 |
| UB-4735 | –21.9 | 0.2 | –20.1 | 0.1 | 30/01/2002 |
| UB-4736 | –22.6 | 0.2 | –20.2 | 0.1 | 31/01/2002 |
| UB-4739 | –21.9 | 0.2 | –20.5 | 0.1 | 01/02/2002 |
| UB-4796 | –21.0 | 0.2 | –21.0 | 0.1 | 30/04/2002 |
| UB-4797 | –20.6 | 0.2 | –20.6 | 0.1 | 02/05/2002 |
| UB-4798 | –20.7 | 0.2 | –19.6 | 0.1 | 10/05/2002 |
| UB-4799 | –19.3 | 0.2 | –18.4 | 0.1 | 13/05/2002 |
| UB-4800 | –21.2 | 0.2 | –20.2 | 0.1 | 14/05/2002 |

| | | | | | |
|---|---|---|---|---|---|
| UB-4801 | –21.8 | 0.2 | –20.3 | 0.1 | 15/05/2002 |
| UB-4802 | –22.8 | 0.2 | –19.3 | 0.1 | 17/05/2002 |
| UB-4803 | –22.6 | 0.2 | –19.5 | 0.1 | 21/05/2002 |
| UB-4835 | –21.3 | 0.2 | –20.4 | 0.1 | 24/09/2002 |
| UB-4836 | –22.0 | 0.2 | –19.5 | 0.1 | 17/09/2002 |
| Laboratory Number | Belfast | | Rafter | | Date converted to $C_6H_6$ |
| | $\delta^{13}C$ (‰) | error (‰) | $\delta^{13}C$ (‰) | error (‰) | |
| UB-4882 | –24.6 | 0.2 | –21.3 | 0.1 | 20/02/2003 |
| UB-4883 | –26.3 | 0.2 | –21.3 | 0.1 | 21/02/2003 |
| UB-4884 | –21.2 | 0.2 | –21.3 | 0.1 | 03/03/2003 |
| UB-4885 | –20.9 | 0.2 | –20.9 | 0.1 | 05/03/2003 |
| UB-4886 | –22.4 | 0.2 | –21.0 | 0.1 | 06/03/2003 |
| UB-4887 | –22.7 | 0.2 | –21.5 | 0.1 | 18/03/2003 |
| UB-4888 | –23.9 | 0.2 | –21.4 | 0.1 | 14/03/2003 |
| UB-4889 | –23.6 | 0.2 | –21.2 | 0.1 | 13/03/2003 |
| UB-4890 | –23.6 | 0.2 | –21.8 | 0.1 | 11/03/2003 |
| UB-4920 | –20.1 | 0.2 | –20.2 | 0.1 | 25/08/2003 |
| UB-4921 | –20.4 | 0.2 | –20.1 | 0.1 | 04/07/2003 |
| UB-4922 | –23.2 | 0.2 | –20.9 | 0.1 | 07/07/2003 |
| UB-4923 | –24.4 | 0.2 | –20.6 | 0.1 | 23/07/2003 |
| UB-4924 | –21.6 | 0.2 | –19.4 | 0.1 | 25/07/2003 |
| UB-4925 | –20.1 | 0.2 | –19.5 | 0.1 | 28/07/2003 |
| UB-4927 | –19.4 | 0.2 | –20.2 | 0.1 | 19/08/2003 |
| UB-4928 | –19.7 | 0.2 | –20.2 | 0.1 | 20/08/2003 |
| UB-4929 | –19.7 | 0.2 | –19.7 | 0.1 | 21/08/2003 |
| UB-4930 | –19.7 | 0.2 | –19.2 | 0.1 | 27/08/2003 |
| UB-4931 | –21.9 | 0.2 | –19.9 | 0.1 | 28/08/2003 |
| UB-4961 | –20.6 | 0.2 | –18.9 | 0.1 | 15/10/2003 |
| UB-4962 | –19.8 | 0.2 | –19.0 | 0.1 | 16/10/2003 |
| UB-4963 | –21.7 | 0.2 | –19.1 | 0.1 | 20/10/2003 |
| UB-4964 | –20.9 | 0.2 | –19.6 | 0.1 | 21/10/2003 |
| UB-4965 | –28.8 | 0.2 | –20.7 | 0.1 | 22/10/2003 |
| UB-4975 | –22.9 | 0.2 | –20.3 | 0.1 | 06/11/2003 |
| UB-4976 | –21.2 | 0.2 | –19.7 | 0.1 | 07/11/2003 |
| UB-4981 | –22.2 | 0.2 | –20.1 | 0.1 | 26/11/2003 |
| UB-4982 | –22.7 | 0.2 | –20.6 | 0.1 | 27/11/2003 |
| UB-4984 | –22.8 | 0.2 | –19.6 | 0.1 | 01/12/2003 |
| UB-4985 | –21.1 | 0.2 | –20.2 | 0.1 | 08/12/2003 |
| UB-5208 | –22.1 | 0.2 | –21.0 | 0.1 | 29/09/2005 |
| UB-6032 | –21.6 | 0.2 | –19.7 | 0.1 | 03/02/2004 |
| UB-6033 | –21.8 | 0.2 | –20.0 | 0.1 | 04/02/2004 |
| UB-6034 | –24.3 | 0.2 | –19.9 | 0.1 | 10/03/2004 |
| UB-6035 | –24.5 | 0.2 | –20.3 | 0.1 | 11/03/2004 |
| UB-6036 | –20.6 | 0.2 | –20.3 | 0.1 | 25/03/2003 |
| UB-6037 | –25.1 | 0.2 | –19.7 | 0.1 | 12/03/2004 |
| UB-6038 | –23.5 | 0.2 | –19.9 | 0.1 | 26/03/2004 |

| | | | | | |
|---|---|---|---|---|---|
| UB-6040 | –22.2 | 0.2 | –19.9 | 0.1 | 20/04/2004 |
| UB-6041 | –23.3 | 0.2 | –20.2 | 0.1 | 21/04/2004 |
| UB-6042 | –21.4 | 0.2 | –19.4 | 0.1 | 22/04/2004 |
| UB-6142 | –22.8 | 0.2 | –17.2 | 0.1 | 26/04/2004 |
| UB-6143 | –18.3 | 0.2 | –16.8 | 0.1 | 27/04/2004 |
| UB-6144 | –19.7 | 0.2 | –17.6 | 0.1 | 28/04/2004 |
| UB-6179 | –22.1 | 0.2 | –20.1 | 0.1 | 01/06/2004 |
| UB-6180 | –22.4 | 0.2 | –20.1 | 0.1 | 02/06/2004 |
| UB-6181 | –24.7 | 0.2 | –20.1 | 0.1 | 08/06/2004 |
| Laboratory Number | Belfast | | Rafter | | Date converted to $C_6H_6$ |
| | $\delta^{13}C$ (‰) | error (‰) | $\delta^{13}C$ (‰) | error (‰) | |
| UB-6182 | –21.1 | 0.2 | –19.4 | 0.1 | 09/06/2004 |
| UB-6183 | –21.5 | 0.2 | –19.8 | 0.1 | 10/06/2004 |
| UB-6184 | –23.7 | 0.2 | –20.0 | 0.1 | 14/06/2004 |
| UB-6185 | –23.7 | 0.2 | –21.9 | 0.1 | 23/04/2004 |
| UB-6345 | –22.3 | 0.2 | –19.5 | 0.1 | 10/11/2004 |
| UB-6346 | –20.7 | 0.2 | –19.0 | 0.1 | 09/11/2004 |
| UB-6347 | –22.8 | 0.2 | –19.7 | 0.1 | 22/11/2004 |
| UB-6472 | –22.3 | 0.2 | –19.7 | 0.1 | 25/05/2005 |
| UB-6473 | –21.4 | 0.2 | –19.5 | 0.1 | 26/05/2005 |
| UB-6474 | –20.9 | 0.2 | –19.8 | 0.1 | 08/06/2005 |
| UB-6475 | –20.5 | 0.2 | –19.9 | 0.1 | 27/05/2005 |
| UB-6476 | –21.3 | 0.2 | –19.6 | 0.1 | 30/05/2005 |
| UB-6477 | –21.0 | 0.2 | –19.5 | 0.1 | 09/06/2005 |
| UB-6479 | –20.7 | 0.2 | –19.5 | 0.1 | 04/07/2005 |
| UB-6534 | –20.0 | 0.2 | –19.1 | 0.1 | 29/06/2006 |

## pre-October 2001

Number of comparisons = 34
Average difference = 0.05
Average standard deviation in difference = 1.71
Mean difference = 0.07 ± 0.04
Standard deviation (=square root of sample variance) = 0.54
k = Standard deviation/Average standard deviation in difference = 2.40

## post-October 2001

Number of comparisons = 91
Average difference = -1.87
Average standard deviation in difference = 1.46
Mean difference = -1.87± 0.02
Standard deviation (=square root of sample variance) = 1.46
k = Standard deviation/Average standard deviation in difference = 6.54

*Table 13: Replicate $\delta^{13}C$ values for wood cellulose, combusted using flow-through combustion and closed tube combustion*

| Laboratory Number | $\delta^{13}C$ (‰) flow-through combustion | $\delta^{13}C$ (‰) closed-tube combustion |
|---|---|---|
| UB-4385 | –23.980 | –23.554 |
| UB-4386 | –24.124 | –23.554 |
| UB-4389 | –24.306 | –23.881 |
| UB-4390 | –24.215 | –23.881 |
| UB-4391 | –24.343 | –23.774 |
| UB-4392 | –24.338 | –23.774 |
| UB-4393 | –24.715 | –24.189 |
| UB-4394 | –24.709 | –24.189 |
| UB-4395 | –24.984 | –24.203 |
| UB-4396 | –25.091 | –24.203 |
| UB-4397 | –25.012 | –24.415 |
| UB-4398 | –25.418 | –24.415 |
| UB-4399 | –25.982 | –25.459 |
| UB-4400 | –25.957 | –25.459 |
| UB-4401 | –25.556 | –25.395 |
| UB-4402 | –25.503 | –25.395 |
| UB-4407 | –25.229 | –24.477 |
| UB-4408 | –25.208 | –24.477 |
| UB-4409/4410 | –25.457 | –24.807 |
| UB-5070 | –24.537 | –24.055 |
| UB-5072 | –24.940 | –24.385 |
| UB-5076 | –25.141 | –24.718 |
| UB-5080 | –25.349 | –24.449 |
| UB-5082 | –24.816 | –24.47 |
| UB-5084 | –25.337 | –24.813 |
| UB-5136 | –26.667 | –25.685 |
| UB-5150 | –27.127 | –26.216 |
| UB-5160 | –25.774 | –25.235 |
| UB-5170 | –24.056 | –23.493 |
| UB-5172 | –23.793 | –23.417 |
| UB-5174 | –23.792 | –23.234 |

Number of comparisons = 30

Mean difference = 0.57 ± 0.01

Standard deviation (=square root of sample variance) = 0.2

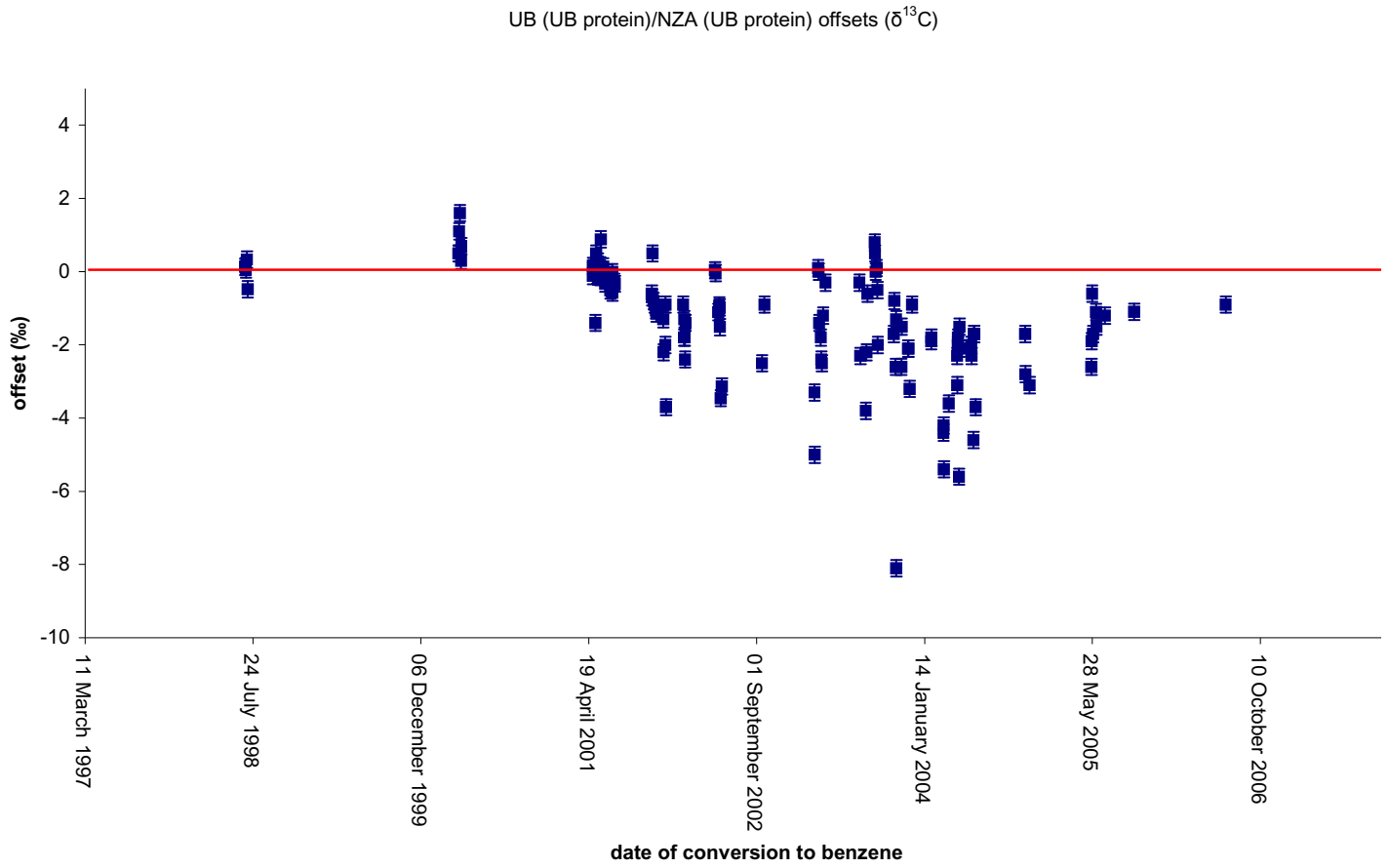


*Figure 24: Replicate $\delta^{13}C$ values measured by Queen's University Belfast and Isotrace New Zealand on samples of bone protein extracted at Belfast*

The difference cannot be attributed to the bone preparation, since $\delta^{13}C$ values for 40 samples are available from Isotrace New Zealand, on both the protein extracted in Belfast and the gelatin processed at Rafter (Table 14). All these samples were processed for dating after October 2001. The mean difference between these sets of results is 0.49±0.27‰, suggesting that the differences observed in Figure 24 do not derive from methods of sample preparation.

*Table 14: $\delta^{13}C$ values measured by Isotrace New Zealand from bone protein extracted in Belfast and bone gelatin prepared at the Rafter Radiocarbon Laboratory from the same samples*

| | Isotrace New Zealand from Belfast protein | | Isotrace New Zealand from Rafter gelatin | |
|---|---|---|---|---|
| Laboratory Number | $\delta^{13}C$ (‰) | error (‰) | $\delta^{13}C$ (‰) | total error (‰) |
| UB-4961 | –18.9 | 0.1 | –19.5 | 0.32 |
| UB-4962 | –19.0 | 0.1 | –19.9 | 0.32 |
| UB-4963 | –19.1 | 0.1 | –19.8 | 0.32 |
| UB-4964 | –19.6 | 0.1 | –20.4 | 0.32 |
| UB-4965 | –20.7 | 0.1 | –20.6 | 0.32 |
| UB-4975 | –20.3 | 0.1 | –20.8 | 0.32 |
| UB-4976 | –19.7 | 0.1 | –20.4 | 0.32 |
| UB-4981 | –20.1 | 0.1 | –20.3 | 0.32 |
| UB-4982 | –20.6 | 0.1 | –20.7 | 0.32 |
| UB-4983 | –19.9 | 0.1 | –20.7 | 0.32 |
| UB-4984 | –19.6 | 0.1 | –20.4 | 0.32 |
| UB-4985 | –20.2 | 0.1 | –20.8 | 0.32 |
| UB-5208 | –21.0 | 0.1 | –20.3 | 0.36 |
| UB-6032 | –19.7 | 0.1 | –20.9 | 0.32 |
| UB-6033 | –20.0 | 0.1 | –20.8 | 0.32 |
| UB-6034 | –19.9 | 0.1 | –20.9 | 0.32 |
| UB-6035 | –20.3 | 0.1 | –21.3 | 0.32 |
| UB-6036 | –20.3 | 0.1 | –20.9 | 0.32 |
| UB-6037 | –19.7 | 0.1 | –20.6 | 0.32 |
| UB-6038 | –19.9 | 0.1 | –21.0 | 0.32 |
| UB-6040 | –19.9 | 0.1 | –21.1 | 0.32 |
| UB-6041 | –20.2 | 0.1 | –20.5 | 0.32 |
| UB-6042 | –19.4 | 0.1 | –20.3 | 0.32 |
| UB-6179 | –20.1 | 0.1 | –20.4 | 0.32 |
| UB-6180 | –20.1 | 0.1 | –20.4 | 0.32 |
| UB-6181 | –20.1 | 0.1 | –20.0 | 0.32 |
| UB-6182 | –19.4 | 0.1 | –19.9 | 0.32 |
| UB-6183 | –19.8 | 0.1 | –20.4 | 0.32 |
| UB-6184 | –20.0 | 0.1 | –20.0 | 0.32 |
| UB-6345 | –19.5 | 0.1 | –19.5 | 0.36 |
| UB-6346 | –19.0 | 0.1 | –19.0 | 0.36 |
| UB-6347 | –19.7 | 0.1 | –19.8 | 0.36 |

| | | | | |
|---|---|---|---|---|
| UB-6472 | –19.7 | 0.1 | –19.8 | 0.36 |
| UB-6473 | –19.5 | 0.1 | –19.8 | 0.36 |
| UB-6474 | –19.8 | 0.1 | –19.7 | 0.36 |
| | Isotrace New Zealand from Belfast protein | | Isotrace New Zealand from Rafter gelatin | |
| Laboratory Number | $\delta^{13}C$ (‰) | error (‰) | $\delta^{13}C$ (‰) | total error (‰) |
| UB-6475 | –19.9 | 0.1 | –19.8 | 0.36 |
| UB-6476 | –19.6 | 0.1 | –19.7 | 0.36 |
| UB-6477 | –19.5 | 0.1 | –19.8 | 0.36 |
| UB-6479 | –19.5 | 0.1 | –19.5 | 0.36 |
| UB-6534 | –19.1 | 0.1 | –19.4 | 0.36 |

Number of comparisons = 40
Average difference = 0.44
Average standard deviation in difference = 1.70
Mean difference = 0.49 ± 0.27
Standard deviation (=square root of sample variance) = 0.44
k = Standard deviation/Average standard deviation in difference = 0.26

Comparison of the $\delta^{13}C$ values for wood samples measured during the period of the Anglo-Saxon project with those measured earlier at Belfast suggests that the mass spectrometer produced accurate results across the entire measurement period. McCormac *et al* (1994) report $\delta^{13}C$ values on 269 samples of Irish bog oak, which have a mean value of -25.9±0.9‰. Forty-eight samples of Irish oak were dated between 1999 and October 2001, which have a mean value of -24.8±0.6‰ (Table 15), and 36 samples were dated after October 2001, which have a mean value of -25.3±0.7‰ (Table 16). These mean values are not statistically significantly different ($T'=1.0$; $T'(5\%)=6.0$; $\nu=2$), suggesting that the $\delta^{13}C$ values measured on oak samples in Belfast do not vary more than would be expected from natural variability between trees. Internal laboratory standards (IAEA C3 cellulose and NBS Oxalic Acid II) also did not show significant deviations from the expected values.

*Table 15: $\delta^{13}C$ values on wood cellulose prepared and measured in Belfast before October 2001*

| Laboratory code | Date measured | $\delta^{13}C$ (‰) |
|---|---|---|
| UB-4379 | 24/06/1999 | –23.79 |
| UB-4380 | 24/06/1999 | –23.79 |
| UB-4381 | 24/06/1999 | –24.83 |
| UB-4382 | 24/06/1999 | –24.68 |
| UB-4383 | 24/06/1999 | –24.58 |
| UB-4384 | 24/06/1999 | –24.61 |
| UB-4385 | 17/06/1999 | –23.98 |
| UB-4386 | 17/06/1999 | –24.12 |
| UB-4387 | 17/06/1999 | –23.81 |
| UB-4388 | 26/05/1999 | –23.85 |
| UB-4389 | 30/04/1999 | –24.31 |
| UB-4390 | 30/04/1999 | –24.22 |
| UB-4391 | 30/04/1999 | –24.34 |
| UB-4392 | 30/04/1999 | –24.34 |
| UB-4393 | 21/04/1999 | –24.72 |
| UB-4394 | 21/04/1999 | –24.71 |
| UB-4395 | 21/04/1999 | –24.98 |
| UB-4396 | 21/04/1999 | –25.09 |
| UB-4397 | 21/04/1999 | –25.01 |
| UB-4398 | 21/04/1999 | –25.42 |
| UB-4399 | 29/02/1999 | –25.98 |
| UB-4400 | 19/02/1999 | –25.96 |
| UB-4401 | 19/02/1999 | –25.56 |
| UB-4402 | 19/02/1999 | –25.50 |
| UB-4403 | 19/02/1999 | –25.73 |
| UB-4404 | 19/02/1999 | –25.81 |
| UB-4405 | 19/02/1999 | –25.73 |
| UB-4406 | 11/02/1999 | –25.90 |
| UB-4407 | 11/02/1999 | –25.23 |
| UB-4408 | 11/02/1999 | –25.21 |
| UB-4409 | 11/02/1999 | –25.46 |
| UB-4410 | 11/02/1999 | –25.46 |
| UB-4616 | 07/03/2001 | –24.45 |
| UB-4617 | 22/03/2001 | –24.43 |
| UB-4618 | 22/03/2001 | –24.60 |
| UB-4619 | 22/03/2001 | –24.85 |
| UB-4620 | 22/03/2001 | –23.95 |
| UB-4621 | 22/03/2001 | –24.25 |
| UB-4622 | 22/03/2001 | –24.54 |
| UB-4623 | 22/03/2001 | –24.54 |
| UB-4624 | 22/03/2001 | –24.77 |
| UB-4625 | 22/03/2001 | –24.65 |
| UB-4626 | 22/03/2001 | –24.54 |

| | | |
|---|---|---|
| UB-4627 | 02/04/2001 | –24.98 |
| UB-4628 | 02/04/2001 | –25.18 |
| UB-4629 | 02/04/2001 | –24.99 |
| UB-4630 | 02/04/2001 | –25.06 |
| Laboratory code | Date measured | $\delta^{13}C$ (‰) |
| UB-4631 | 02/04/2001 | –24.98 |

Number of comparisons = 48
Mean = 24.82 ± 0.03
Standard deviation (=square root of sample variance) = 0.61

*Table 16: $\delta^{13}C$ values on wood cellulose prepared and measured in Belfast after October 2001*

| Laboratory code | Date measured | $\delta^{13}C$ (‰) |
|---|---|---|
| UB-4933 | 22/07/2003 | –26.23 |
| UB-4934 | 22/07/2003 | –26.23 |
| UB-4935 | 22/07/2003 | –25.84 |
| UB-4936 | 22/07/2003 | –25.84 |
| UB-4937 | 06/08/2003 | –24.87 |
| UB-4938 | 06/08/2003 | –24.87 |
| UB-4939 | 06/08/2003 | –23.87 |
| UB-4940 | 06/08/2003 | –23.87 |
| UB-4941 | 06/08/2003 | –24.81 |
| UB-4942 | 06/08/2003 | –24.81 |
| UB-4943 | 06/08/2003 | –24.38 |
| UB-4944 | 06/08/2003 | –24.38 |
| UB-4945 | 05/09/2003 | –25.28 |
| UB-4946 | 05/09/2003 | –25.28 |
| UB-4947 | 05/09/2003 | –24.68 |
| UB-4948 | 05/09/2003 | –24.68 |
| UB-4949 | 18/09/2003 | –25.39 |
| UB-4950 | 18/09/2003 | –25.39 |
| UB-4951 | 18/09/2003 | –24.88 |
| UB-4952 | 18/09/2003 | –24.88 |
| UB-6107 | 07/04/2004 | –25.15 |
| UB-6108 | 07/04/2004 | –25.15 |
| UB-6109 | 19/03/2004 | –25.00 |
| UB-6110 | 06/07/2005 | –25.78 |
| UB-6111 | 06/07/2005 | –26.33 |
| UB-6112 | 18/09/2005 | –25.93 |
| UB-6113 | 06/07/2005 | –26.94 |
| UB-6114 | 18/09/2005 | –25.86 |
| UB-6115 | 04/10/2005 | –25.00 |
| UB-6116 | 04/10/2005 | –25.00 |
| UB-6117 | 18/09/2005 | –26.19 |
| UB-6118 | 18/09/2005 | –26.30 |
| UB-6119 | 18/09/2005 | –25.77 |

| | | |
|---|---|---|
| UB-6120 | 18/09/2005 | –25.80 |
| UB-6121 | 18/09/2005 | –25.66 |
| UB-6122 | 18/09/2005 | –25.71 |

Number of comparisons = 36

Mean = -25.34 ± 0.03

Standard deviation (=square root of sample variance) = 0.71

The reproducibility of $\delta^{13}C$ values measured in New Zealand on replicate samples of bone gelatinized at the Rafter Radiocarbon Laboratory is demonstrated by a series of replicate measurements (Table 17). All pairs are statistically consistent (at 95% confidence).

*Table 17: $\delta^{13}C$ values measured at Isotrace New Zealand from replicate samples of bone separately gelatinized at the Rafter Radiocarbon Laboratory (T'(5%)=3.8; v=1 for all pairs)*

| Laboratory Number | Grave | $\delta^{13}C$ (‰) Total error | $\delta^{13}C$ (‰) Total error | T' |
|---|---|---|---|---|
| UB-4965/UB-6344 | Appledown Compton, grave 117 | –20.60±0.32 | –20.2±0.36 | 0.7 |
| UB-4879 | Lundenwic: ROH90, grave 31 | –20.80±0.32 | –20.18±0.32 | 1.9 |
| UB-4930/UB-6346 | St Peter's Tip, grave 42 | –19.40±0.32 | –19.00±0.36 | 0.7 |
| UB-4925 | St Peter's Tip, grave 68 | –19.47±0.32 | –19.28±0.32 | 0.2 |
| UB-4924/UB-6534 | St Peter's Tip, grave 113 | –19.70±0.32 | –19.40±0.36 | 0.4 |
| UB-4927 | St Peter's Tip, grave 263 | –19.76±0.32 | –19.67±0.32 | 0.0 |
| UB-6472 | Dover Buckland, grave 222 | –19.80±0.36 | –20.08±0.32 | 0.3 |
| UB-6474 | Dover Buckland, grave 264 | –19.70±0.36 | –19.97±0.32 | 0.3 |
| UB-4923 | Edix Hill, grave 7 | –20.30±0.32 | –20.35±0.32 | 0.0 |
| UB-4511 | Edix Hill, grave 90 | –20.10±0.32 | –20.65±0.32 | 1.5 |
| UB-4886/UB-6345 | Melbourne, SK 1204 SG77 | –20.00±0.32 | –19.50±0.36 | 1.1 |
| UB-4885 | Melbourne, InL 1189 SG78 | –20.10±0.32 | –20.49±0.32 | 0.7 |
| UB-4884 | Melbourne, SK1188 SG79 | –20.40±0.32 | –20.38±0.32 | 0.0 |
| UB-4984 | Lechlade, grave 18 | –20.40±0.32 | –20.60±0.32 | 0.2 |
| UB-4683 | Lechlade, grave 40 | –19.70±0.36 | –20.47±0.32 | 2.6 |

It is apparent, nonetheless, that the $\delta^{13}C$ measurements on bone samples from October 2001 gradually show a greater offset between Belfast and New Zealand (Fig 24). In 2005 the VG 602e Micromass in the Belfast Radiocarbon Laboratory was serviced and found to be poorly focused. The mass spectrometer focus problem combined with sulphur contamination in some of the bone samples caused measurements on such samples to be inaccurate. Unfortunately material was not available to allow a sufficient number of re-measurements to be made to demonstrate this unequivocally.

A bias in measured $\delta^{13}C$ values of the magnitude shown in Figure 24 would make radiocarbon ages calculated using the anomalous values substantively too young. For this reason, the radiocarbon ages reported here have been calculated using $\delta^{13}C$ values measured in Belfast only for samples converted to benzene before October 2001.

Radiocarbon ages for samples processed after October 2001 cannot be calculated on the basis of these values. We have seen that the $\delta^{13}C$ values on the dated protein measured in Belfast and New Zealand are in very good agreement before October 2001 (mean difference = 0.07±0.54‰). Unfortunately $\delta^{13}C$ values on this material measured in New Zealand are only available for 79% of the samples run after October 2001, and so these

cannot be used to calculate radiocarbon ages for all the affected samples. For this reason radiocarbon ages for these samples have been calculated using the $\delta^{13}C$ values from bone gelatin prepared at the Rafter Radiocarbon Laboratory and measured at Isotrace New Zealand . These values have been offset by the mean difference between the $\delta^{13}C$ values measured in Belfast on the dated protein and the $\delta^{13}C$ values measured in New Zealand on bone gelatin prepared at Rafter from the same samples in the period before October 2001. These datasets are also in good agreement (Fig 25) and, although the mean difference between them is slightly larger (–0.25±0.39‰; Table 18), the use of $\delta^{13}C$ values from bone gelatinized in New Zealand rather than from the dated protein in practice shifts the calculated radiocarbon ages by less than a year. The total measurement error on the $\delta^{13}C$ values used to calculate these radiocarbon ages was taken as the square root of the sum of the squares of the total error estimate quoted by New Zealand and the standard deviation on the mean offset.

The $\delta^{13}C$ values used to calculate all the radiocarbon ages reported here are shown in Table 11. Stable isotope values more appropriate for dietary studies are reported in Beavan *et al* (2011).

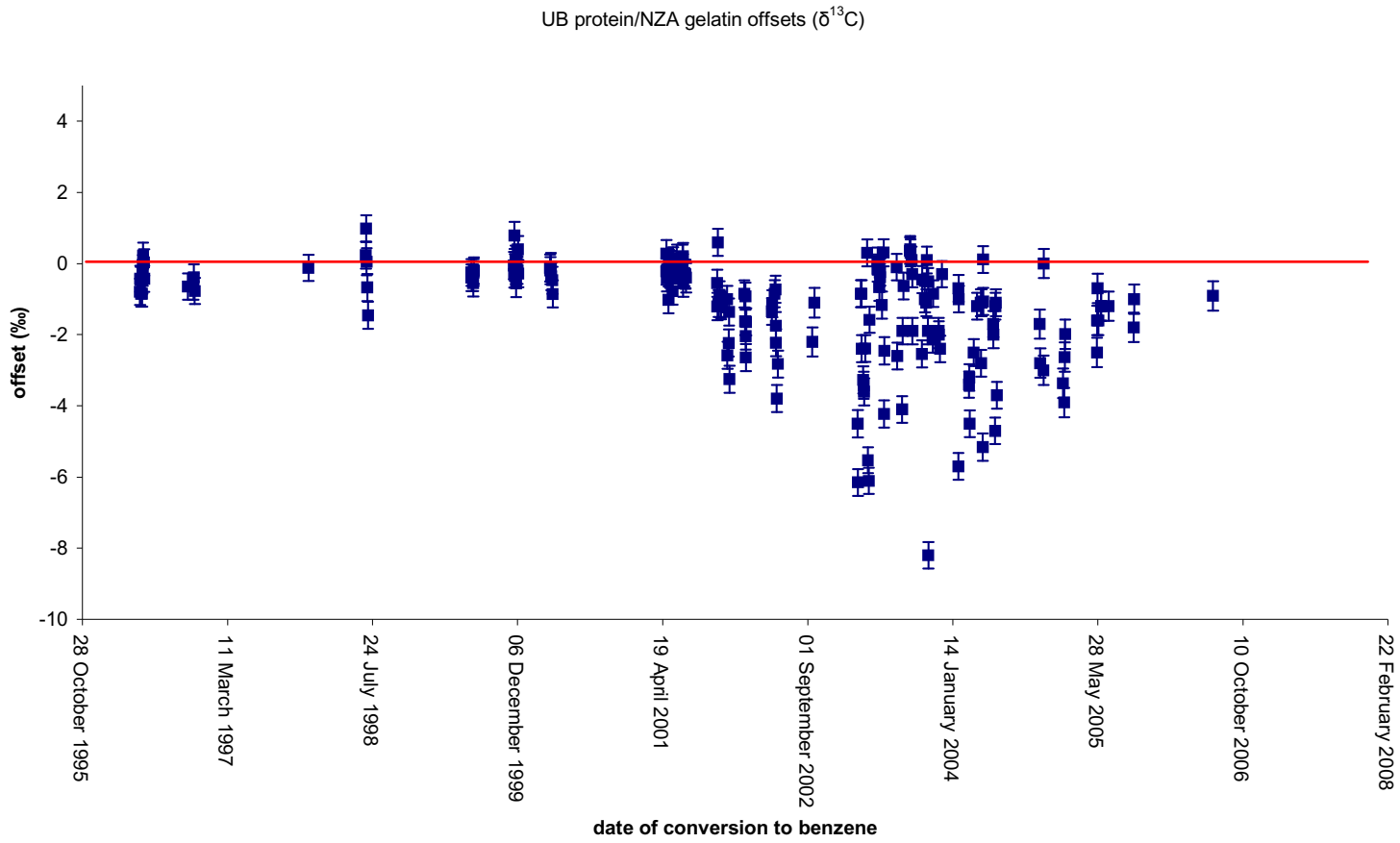


*Figure 25: $\delta^{13}C$ values measured at Belfast on the protein extracted for radiocarbon dating and $\delta^{13}C$ values measured by Isotrace New Zealand on gelatin prepared by the Rafter Radiocarbon Laboratory from the same samples*

*Table 18: $\delta^{13}C$ values measured in Belfast on the bone protein extracted for radiocarbon dating and $\delta^{13}C$ values measured at Isotrace New Zealand on bone gelatin prepared from the same samples at the Rafter Radiocarbon Laboratory*

| | | Belfast | | New Zealand | |
|---|---|---|---|---|---|
| Laboratory Number | | $\delta^{13}C$(‰) | error (‰) | $\delta^{13}C$(‰) | total error (‰) |
| UB-4039 | Buttermarket, grave 3871 | –20.9 | 0.2 | –20.1 | 0.31 |
| UB-4040 | Buttermarket, grave 3897 | –20.1 | 0.2 | –19.7 | 0.31 |
| UB-4041 | Buttermarket, grave 249 | –20.3 | 0.2 | –19.8 | 0.31 |
| UB-4042 | Buttermarket, grave 1674 | –21.3 | 0.2 | –20.5 | 0.31 |
| UB-4043 | Buttermarket, grave 2365 | –20.9 | 0.2 | –20.1 | 0.31 |
| UB-4044 | Buttermarket, grave 4152 | –20.3 | 0.2 | –19.8 | 0.31 |
| UB-4045 | Buttermarket, grave 4307 | –19.5 | 0.2 | –19.2 | 0.31 |
| UB-4046 | Buttermarket, grave 4344 | –20.2 | 0.2 | –20.1 | 0.31 |
| UB-4047 | Buttermarket, grave 4431 | –19.7 | 0.2 | –19.9 | 0.31 |
| UB-4048 | Buttermarket, grave 4926 | –20.1 | 0.2 | –20.1 | 0.31 |
| UB-4049 | Buttermarket, grave 4979 | –20.5 | 0.2 | –20.1 | 0.31 |
| UB-4074 | Buttermarket, grave 2297 | –20.6 | 0.2 | –20.0 | 0.31 |
| UB-4075 | Buttermarket, grave 3898 | –20.0 | 0.2 | –19.4 | 0.31 |
| UB-4076 | Buttermarket, grave 4269 | –20.4 | 0.2 | –20.0 | 0.31 |
| UB-4077 | Buttermarket, grave 4275 | –21.0 | 0.2 | –20.2 | 0.31 |
| UB-4210 | Buttermarket, grave 1760 | –19.9 | 0.2 | –19.8 | 0.31 |
| UB-4306 | Known-age bone, sample 1 | –18.6 | 0.2 | –18.8 | 0.32 |
| UB-4307 | Known-age bone, sample 2 | –18.6 | 0.2 | –19.6 | 0.32 |
| UB-4308 | Known-age bone, sample 3 | –18.3 | 0.2 | –18.4 | 0.32 |
| UB-4309 | Known-age bone, sample 4 | –18.3 | 0.2 | –17.6 | 0.32 |
| UB-4310 | Known-age bone, sample 5 | –20.3 | 0.2 | –18.8 | 0.32 |
| UB-4440 | Barton on Humber BH14 | –20.0 | 0.2 | –19.8 | 0.32 |
| UB-4441 | Barton on Humber BH15 | –20.1 | 0.2 | –19.7 | 0.32 |
| UB-4442 | Barton on Humber BH16 | –20.4 | 0.2 | –20.0 | 0.32 |
| UB-4443 | Barton on Humber BH17 | –19.6 | 0.2 | –19.1 | 0.32 |
| UB-4444 | Barton on Humber BH 18 | –19.9 | 0.2 | –19.7 | 0.32 |
| UB-4445 | Barton on Humber BH 19 | –19.9 | 0.2 | –19.7 | 0.32 |
| UB-4501 | Lechlade: grave 14 | –20.0 | 0.2 | –19.9 | 0.32 |
| UB-4502 | Lechlade: grave 138 | –20.4 | 0.2 | –20.1 | 0.32 |
| UB-4503 | Lechlade: grave 148 | –19.3 | 0.2 | –20.1 | 0.32 |
| UB-4504 | Lechlade: grave 179 | –20.3 | 0.2 | –20.2 | 0.32 |
| UB-4505 | Lechlade: grave 172/1 | –20.2 | 0.2 | –20.3 | 0.32 |
| UB-4506 | Lechlade: grave 172/2 | –20.2 | 0.2 | –20.0 | 0.32 |
| UB-4507 | Lechlade: grave 187 | –20.2 | 0.2 | –19.6 | 0.32 |
| UB-4508 | Edix Hill: grave 12 | –20.2 | 0.2 | –20.0 | 0.32 |
| UB-4509 | Edix Hill: grave 33 | –20.1 | 0.2 | –20.2 | 0.32 |
| UB-4510 | Edix Hill: grave 48 | –20.2 | 0.2 | –20.6 | 0.32 |
| UB-4511 | Edix Hill: grave 90 | –20.3 | 0.2 | –20.1 | 0.32 |
| UB-4512 | Edix Hill: grave 91 | –20.5 | 0.2 | –20.2 | 0.32 |
| UB-4549 | Marina Drive: grave C7 | –20.6 | 0.2 | –20.4 | 0.32 |

| | | | | | |
|---|---|---|---|---|---|
| UB-4550 | Marina Drive: grave E1 | –20.0 | 0.2 | –19.9 | 0.32 |
| UB-4551 | Marina Drive: grave E2 | –20.3 | 0.2 | –20.2 | 0.32 |
| UB-4552 | Marina Drive: grave E3 | –20.5 | 0.2 | –20.1 | 0.32 |
| UB-4553 | Marina Drive: grave D10 | –20.8 | 0.2 | –20.3 | 0.32 |
| | | Belfast | | New Zealand | |
| Laboratory Number | | $\delta^{13}C$(‰) | error (‰) | $\delta^{13}C$(‰) | total error (‰) |
| UB-4554 | Marina Drive: grave F2 | –20.8 | 0.2 | –19.9 | 0.32 |
| UB-4641 | West Heslerton, grave 71 | –20.0 | 0.2 | –19.8 | 0.32 |
| UB-4642 | West Heslerton, grave 72 | –19.9 | 0.2 | –20.2 | 0.32 |
| UB-4643 | Castledyke South, grave 5 | –20.3 | 0.2 | –19.9 | 0.32 |
| UB-4644 | Castledyke South, grave 15 | –21.3 | 0.2 | –20.3 | 0.32 |
| UB-4645 | Castledyke South, grave 54 | –19.9 | 0.2 | –19.9 | 0.32 |
| UB-4646 | Castledyke South, grave 84 | –20.2 | 0.2 | –19.9 | 0.32 |
| UB-4647 | Barton on Humber BH23 | –18.8 | 0.2 | –18.8 | 0.32 |
| UB-4648 | Barton on Humber BH25 | –19.9 | 0.2 | –19.8 | 0.32 |
| UB-4649 | Barton on Humber BH27 | –20.1 | 0.2 | –20.0 | 0.32 |
| UB-4650 | Barton on Humber BH28 | –19.9 | 0.2 | –19.2 | 0.32 |
| UB-4651 | Barton on Humber BH29 | –19.4 | 0.2 | –19.1 | 0.32 |
| UB-4652 | Barton on Humber BH31 | –19.4 | 0.2 | –19.5 | 0.32 |
| UB-4653 | Barton on Humber BH33 | –20.0 | 0.2 | –19.9 | 0.32 |
| UB-4654 | Barton on Humber BH34 | –19.7 | 0.2 | –19.6 | 0.32 |
| UB-4655 | Barton on Humber BH35 | –19.8 | 0.2 | –19.9 | 0.32 |
| UB-4656 | Barton on Humber BH36 | –20.0 | 0.2 | –19.9 | 0.32 |
| UB-4657 | Barton on Humber BH37 | –19.5 | 0.2 | –19.4 | 0.32 |
| UB-4658 | Barton on Humber BH38 | –19.5 | 0.2 | –19.7 | 0.32 |
| UB-4659 | Barton on Humber BH39 | –19.4 | 0.2 | –19.3 | 0.32 |
| UB-4660 | Barton on Humber BH40 | –19.5 | 0.2 | –19.7 | 0.32 |
| UB-4661 | Barton on Humber BH41 | –20.4 | 0.2 | –19.8 | 0.32 |
| UB-4662 | Barton on Humber BH72 | –20.0 | 0.2 | –19.8 | 0.32 |
| UB-4663 | Barton on Humber BH73 | –19.2 | 0.2 | –18.9 | 0.32 |
| UB-4682 | Westgarth Gardens: grave 66 | –20.2 | 0.2 | –19.9 | 0.36 |
| UB-4683 | Lechlade: grave 40 | –20.1 | 0.2 | –19.7 | 0.36 |
| UB-4705 | West Heslerton: 002BA 00606 | –20.9 | 0.2 | –20.3 | 0.32 |
| UB-4706 | West Heslerton: 002BA00536 | –21.1 | 0.2 | –19.9 | 0.32 |
| UB-4707 | Edix Hill: grave 79 | –19.7 | 0.2 | –20.3 | 0.32 |
| UB-4708 | Edix Hill: grave 83 | –21.3 | 0.2 | –20.2 | 0.32 |
| UB-4709 | Edix Hill: grave 14 | –21.3 | 0.2 | –20.4 | 0.32 |
| UB-4719 | Barton on Humber BH89 | –20.8 | 0.2 | –19.6 | 0.32 |
| UB-4720 | Barton on Humber BH90 | –20.5 | 0.2 | –19.4 | 0.32 |
| UB-4727 | Gally Hills: primary burial | –21.3 | 0.2 | –20.3 | 0.32 |
| UB-4728 | Mill Hill: grave 64 | –22.1 | 0.2 | –19.5 | 0.32 |
| UB-4729 | Mill Hill: grave 68 | –21.7 | 0.2 | –19.5 | 0.32 |
| UB-4730 | Mill Hill: grave 79 | –20.5 | 0.2 | –19.1 | 0.32 |
| UB-4731 | Mill Hill: grave 93 | –23.1 | 0.2 | –19.8 | 0.32 |
| UB-4732 | Mill Hill: grave 94 | –20.6 | 0.2 | –19.7 | 0.32 |
| UB-4733 | Mill Hill: grave 95 | –21.5 | 0.2 | –19.9 | 0.32 |

| | | | | | |
|---|---|---|---|---|---|
| UB-4734 | Mill Hill: grave 105C | –21.2 | 0.2 | –20.3 | 0.32 |
| UB-4735 | Berinsfield: grave 22 | –21.9 | 0.2 | –19.9 | 0.32 |
| UB-4736 | Berinsfield: grave 28 | –22.6 | 0.2 | –20.0 | 0.32 |
| UB-4739 | Berinsfield: grave 134/1 | –21.9 | 0.2 | –20.3 | 0.32 |
| UB-4796 | Known-age bone, sample 6 | –21.0 | 0.2 | –19.6 | 0.32 |
| UB-4797 | Known-age bone, sample 7 | –20.6 | 0.2 | –19.5 | 0.32 |
| UB-4798 | Known-age bone, sample 8 | –20.7 | 0.2 | –19.9 | 0.32 |
| UB-4799 | Known-age bone, sample 9 | –19.3 | 0.2 | –18.6 | 0.32 |
| | | Belfast | | New Zealand | |
| Laboratory Number | | $\delta^{13}C$(‰) | error (‰) | $\delta^{13}C$(‰) | total error (‰) |
| UB-4800 | Known-age bone, sample 10 | –21.2 | 0.2 | –19.4 | 0.32 |
| UB-4801 | Known-age bone, sample 11 | –21.8 | 0.2 | –19.6 | 0.32 |
| UB-4802 | Known-age bone, sample 12 | –22.8 | 0.2 | –19.0 | 0.32 |
| UB-4803 | Known-age bone, sample 13 | –22.6 | 0.2 | –19.8 | 0.32 |
| UB-4835 | Appledown Compton, grave 134 | –21.3 | 0.2 | –20.2 | 0.36 |
| UB-4836 | Westgarth Gardens, grave 27 | –22.0 | 0.2 | –19.8 | 0.36 |
| UB-4882 | Melbourne: SK1187 SG80 | –24.6 | 0.2 | –20.1 | 0.32 |
| UB-4883 | Melbourne: SK1038, SG95 | –26.3 | 0.2 | –20.1 | 0.32 |
| UB-4884 | Melbourne: SK1188 SG79 | –21.2 | 0.2 | –20.4 | 0.32 |
| UB-4885 | Melbourne, InL1189 SG78 | –20.9 | 0.2 | –20.1 | 0.32 |
| UB-4886 | Melbourne: SK1204 SG77 | –22.4 | 0.2 | –20.0 | 0.32 |
| UB-4887 | Melbourne: SK 1229 SG82 | –22.7 | 0.2 | –20.3 | 0.32 |
| UB-4888 | Melbourne: SK1271 SG89 | –23.9 | 0.2 | –20.3 | 0.32 |
| UB-4889 | Melbourne: SK1293, SG69 | –23.6 | 0.2 | –20.2 | 0.32 |
| UB-4890 | Melbourne: SK1307 SG75 | –23.6 | 0.2 | –20.3 | 0.32 |
| UB-4896 | Claydon Pike FCPA | –25.0 | 0.2 | –19.5 | 0.31 |
| UB-4897 | Claydon Pike FCPB | –25.9 | 0.2 | –19.8 | 0.31 |
| UB-4898 | Claydon Pike FCPC | –21.2 | 0.2 | –19.6 | 0.31 |
| UB-4907 | Bloodmoor Hill: F165 (2304) | –20.0 | 0.2 | –19.9 | 0.32 |
| UB-4908 | Bloodmoor Hill: F173 (1440) | –20.2 | 0.2 | –20.3 | 0.32 |
| UB-4909 | Bloodmoor Hill: F185 (1520) | –20.6 | 0.2 | –20.3 | 0.32 |
| UB-4910 | Bloodmoor Hill: F236 (2280) | –20.6 | 0.2 | –20.2 | 0.32 |
| UB-4911 | Bloodmoor Hill: F241 (2238) | –20.8 | 0.2 | –20.1 | 0.32 |
| UB-4912 | Bloodmoor Hill: F256 (2259) | –20.7 | 0.2 | –20.5 | 0.32 |
| UB-4913 | Bloodmoor Hill: F257 (2260) | –20.4 | 0.2 | –20.7 | 0.32 |
| UB-4914 | Bloodmoor Hill: F261 (2261) | –24.5 | 0.2 | –20.3 | 0.32 |
| UB-4915 | Bloodmoor Hill: F364 (3417) | –22.6 | 0.2 | –20.1 | 0.32 |
| UB-4916 | Bloodmoor Hill: F265 (2269) | –20.8 | 0.2 | –19.6 | 0.32 |
| UB-4920 | replicate of UB-4727 | –20.1 | 0.2 | –20.2 | 0.32 |
| UB-4921 | Mill Hill: grave 81 | –20.4 | 0.2 | –20.3 | 0.32 |
| UB-4922 | replicate of UB-4510 | –23.2 | 0.2 | –20.6 | 0.32 |
| UB-4923 | Edix Hill: grave 7 | –24.4 | 0.2 | –20.3 | 0.32 |
| UB-4924 | St Peter's Tip: grave 113 | –21.6 | 0.2 | –19.7 | 0.32 |
| UB-4925 | St Peter's Tip: grave 68 | –20.1 | 0.2 | –19.47 | 0.32 |
| UB-4927 | St Peter's Tip: grave 263 | –19.4 | 0.2 | –19.76 | 0.32 |
| UB-4928 | St Peter's Tip: grave 250 | –19.7 | 0.2 | –20.1 | 0.32 |

| | | | | | |
|---|---|---|---|---|---|
| UB-4929 | St Peter's Tip: grave 194 | –19.7 | 0.2 | –20 | 0.32 |
| UB-4930 | St Peter's Tip: grave 42 | –19.7 | 0.2 | –19.4 | 0.32 |
| UB-4931 | St Peter's Tip: grave 318 | –21.9 | 0.2 | –20 | 0.32 |
| UB-4958 | Dover Buckland: grave 375 | –22.3 | 0.2 | –19.8 | 0.32 |
| UB-4959 | Dover Buckland: grave 391A | –20.7 | 0.2 | –20.3 | 0.32 |
| UB-4960 | Dover Buckland: grave 391B | –21.0 | 0.2 | –20 | 0.32 |
| UB-4961 | St Peter's Tip: grave 8 | –20.6 | 0.2 | –19.5 | 0.32 |
| UB-4962 | St Peter's Tip: grave 196 | –19.8 | 0.2 | –19.9 | 0.32 |
| UB-4963 | St Peter's Tip: grave 208 | –21.7 | 0.2 | –19.8 | 0.32 |
| UB-4964 | Coddenham: grave 308 | –20.9 | 0.2 | –20.4 | 0.32 |
| UB-4965 | Appledown Compton: grave 117 | –28.8 | 0.2 | –20.6 | 0.32 |
| UB-4975 | Aston Clinton: grave 12 | –22.9 | 0.2 | –20.77 | 0.32 |
| | | Belfast | | New Zealand | |
| Laboratory Number | | $\delta^{13}C$(‰) | error (‰) | $\delta^{13}C$(‰) | total error (‰) |
| UB-4976 | Ford, Laverstock: barrow 2 | –21.2 | 0.2 | –20.35 | 0.32 |
| UB-4981 | Lechlade: grave 183 | –22.2 | 0.2 | –20.3 | 0.32 |
| UB-4982 | Lechlade: grave 155 | –22.7 | 0.2 | –20.7 | 0.32 |
| UB-4984 | Lechlade: grave 18 | –22.8 | 0.2 | –20.4 | 0.32 |
| UB-4985 | Westgarth Gardens: grave 11 | –21.1 | 0.2 | –20.8 | 0.32 |
| UB-5208 | Appledown Compton, grave 107 | –22.1 | 0.2 | –20.3 | 0.36 |
| UB-6031 | Sutton Courtenay, DRST02 163 | –24.5 | 0.2 | –18.8 | 0.32 |
| UB-6032 | St Peter's Tip, grave 73A | –21.6 | 0.2 | –20.9 | 0.32 |
| UB-6033 | West Heslerton, grave 113 | –21.8 | 0.2 | –20.8 | 0.32 |
| UB-6034 | Castledyke South, grave 120 | –24.3 | 0.2 | –20.9 | 0.32 |
| UB-6035 | Castledyke South, grave 96 | –24.5 | 0.2 | –21.3 | 0.32 |
| UB-6036 | Castledyke South, grave 13 | –20.6 | 0.2 | –20.9 | 0.32 |
| UB-6037 | Castledyke South, grave 134 | –25.1 | 0.2 | –20.6 | 0.32 |
| UB-6038 | Castledyke South, grave 183 | –23.5 | 0.2 | –21 | 0.32 |
| UB-6039 | Castledyke South, grave 94 | –21.7 | 0.2 | –20.5 | 0.32 |
| UB-6040 | Castledyke South, grave 53 | –22.2 | 0.2 | –21.1 | 0.32 |
| UB-6041 | Castledyke South, grave 182 | –23.3 | 0.2 | –20.5 | 0.32 |
| UB-6042 | Castledyke South, grave 88 | –21.4 | 0.2 | –20.3 | 0.32 |
| UB-6142 | Known age bone - sample 14 | –22.8 | 0.2 | –17.6 | 0.32 |
| UB-6143 | Known age bone - sample 15 | –18.3 | 0.2 | –18.4 | 0.32 |
| UB-6144 | Known age bone - sample 16 | –19.7 | 0.2 | –18.6 | 0.32 |
| UB-6179 | Riccall Landing, 1974.121 SKE | –22.1 | 0.2 | –20.4 | 0.32 |
| UB-6180 | Riccall Landing, 1974.121 SK18 | –22.4 | 0.2 | –20.4 | 0.32 |
| UB-6181 | Riccall Landing, 1985.11 SK1 | –24.7 | 0.2 | –20 | 0.32 |
| UB-6182 | Riccall Landing, 1985.11 SK17 | –21.1 | 0.2 | –19.9 | 0.32 |
| UB-6183 | Riccall Landing, 1976.27 SKA | –21.5 | 0.2 | –20.4 | 0.32 |
| UB-6184 | Riccall Landing, 1974.121 SK4 | –23.7 | 0.2 | –20 | 0.32 |
| UB-6345 | Melbourne: SK1204 SG77 | –22.3 | 0.2 | –19.5 | 0.36 |
| UB-6346 | St Peter's Tip: grave 42 | –20.7 | 0.2 | –19 | 0.36 |
| UB-6347 | Lakenheath, ERL 104 4222 | –22.8 | 0.2 | –19.8 | 0.36 |
| UB-6348 | Lakenheath, ERL 104 4206 | –22.6 | 0.2 | –22.6 | 0.36 |
| UB-6394 | Crickley Hill CH71 F370 | –25.3 | 0.2 | –21.9 | 0.36 |

| | | | | | |
|---|---|---|---|---|---|
| UB-6395 | Crickley Hill 3396 | –26.0 | 0.2 | –22.1 | 0.36 |
| UB-6396 | Crickley Hill CH77 4517 | –24.7 | 0.2 | –22.1 | 0.36 |
| UB-6397 | Crickley Hill CH77 4582 | –24.3 | 0.2 | –22.3 | 0.36 |
| UB-6472 | Dover Buckland, Grave 222 | –22.3 | 0.2 | –19.8 | 0.36 |
| UB-6473 | Dover Buckland, Grave 250 | –21.4 | 0.2 | –19.8 | 0.36 |
| UB-6474 | Dover Buckland, Grave 264 | –20.9 | 0.2 | –19.7 | 0.36 |
| UB-6475 | Dover Buckland, Grave 323 | –20.5 | 0.2 | –19.8 | 0.36 |
| UB-6476 | Dover Buckland, Grave 339 | –21.3 | 0.2 | –19.7 | 0.36 |
| UB-6477 | Dover Buckland, Grave 414 | –21.0 | 0.2 | –19.8 | 0.36 |
| UB-6478 | St Peter's Tip, Grave 360 | –21.1 | 0.2 | –20.1 | 0.36 |
| UB-6479 | Mill Hill, Grave 40 | –20.7 | 0.2 | –19.5 | 0.36 |
| UB-6534 | St Peter's Tip: grave 113 | –20.0 | 0.2 | –19.4 | 0.36 |

pre-October 2001

Number of comparisons = 70
Average difference = –0.25
Average standard deviation in difference = 0.39
Mean difference = –0.25 ± 0.05
Standard deviation (=square root of sample variance) = 0.39
k = Standard deviation/Average standard deviation in difference = 1.03

post-October 2001
Number of comparisons = 115
Average difference = –1.65
Average standard deviation in difference = 2.59
Mean difference = –1.63 ± 0.04
Standard deviation (=square root of sample variance) = 2.7
k = Standard deviation/Average standard deviation in difference = 7.04

# 11 CONCLUSIONS

This report describes the laboratory techniques used for dating the radiocarbon samples processed at the Belfast Radiocarbon Laboratory for the Anglo-Saxon chronology project. Procedures for fractionation correction and age calculation are also discussed. As part of this project a bespoke section of calibration curve covering the early Anglo-Saxon period was produced. Details of the radiocarbon measurements and the dated tree-ring series from which the samples were taken are also described.

The samples were measured over an eight-year period (1999–2006). The reproducibility of the radiocarbon measurements over this extended period is demonstrated by the excellent agreement between the decadal replicate pairs of known-age wood (Fig 12), and by the good agreement between a limited number of replicate bone samples (Section 8).

The accuracy of these radiocarbon measurements is demonstrated by the similarity of the new calibration data with those produced previously by Pearson *et al* (1986) (Fig 14) and Stuiver and Becker (1986, corrected as reported in Stuiver *et al* (1998a)) (Fig 15). More generally, measurement accuracy is demonstrated by the results reported for international inter-comparison exercises undertaken during this time (Table 10).

The tree-ring measurements were made quasi-simultaneously with the bone samples dated for this project, and so will provide the most accurate calibration of these samples (as, for example, there are no laboratory offsets to be considered). However, these

results will be incorporated for general use in the next international radiocarbon calibration curve (IntCal).

Archaeological evidence also provides some independent confirmation of the relative accuracy of the calibrated dates. Six dated samples can be related to others stratigraphically (Fig 23). In all cases the results are in good agreement with the excavated sequence.

It is more difficult to assess whether the dated bone protein in all cases derived from a purely terrestrial reservoir, as required if measurements on human bone are to be converted accurately to the calendar timescale by tree-ring calibration. A replicate pair of measurements on a horse and human buried together at Lakenheath, however, are statistically consistent (UB-6347–8). This issue is discussed further in Beavan *et al* (2011).

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# NOTES

[1] A third measurement was made on excess pre-treated cellulose from this sample in July 2006. This result is 1283±20 BP (UB-5232); $\delta^{13}C$ −25.2±0.2‰.

[2] The result for the bi-decade centred on AD 710 produced by Pearson *et al* (1986) is 1282±17 BP. This has been confirmed by reference to the primary laboratory archive as the error was previously omitted from the published dataset due to a printing error.

[3] The $\delta^{13}C$ values reported in this table are those used in the calculation of the radiocarbon age (see Section 9). Stable isotope values appropriate for dietary studies are reported and discussed in Beavan *et al* (2011)

[4] Replicate measurements are also available from two burial mounds at Sutton Hoo, Suffolk (Carver 2005, 54–5). The two measurements on bone collagen from a human inhumation and a horse burial from beneath mound 17 are not statistically consistent (UB-4422 and UB-4423; T'=6.5; T'(5%)=3.8; $\nu$=1), almost certainly because of the incomplete removal of a chemical consolidant from the sample of human bone. Results from a sample of beeswax from the iron lamp in the ship burial beneath mound 1 (BM-640) and from a fragment of oak interpreted as part of the burial chamber (BM-688) are also statistically inconsistent (T'=7.1; T'(5%)=3.8; $\nu$=1). Burleigh *et al* (1976, 22) consider BM-688 to be anomalously young because of contamination by younger humic material.

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